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Construction Engineering
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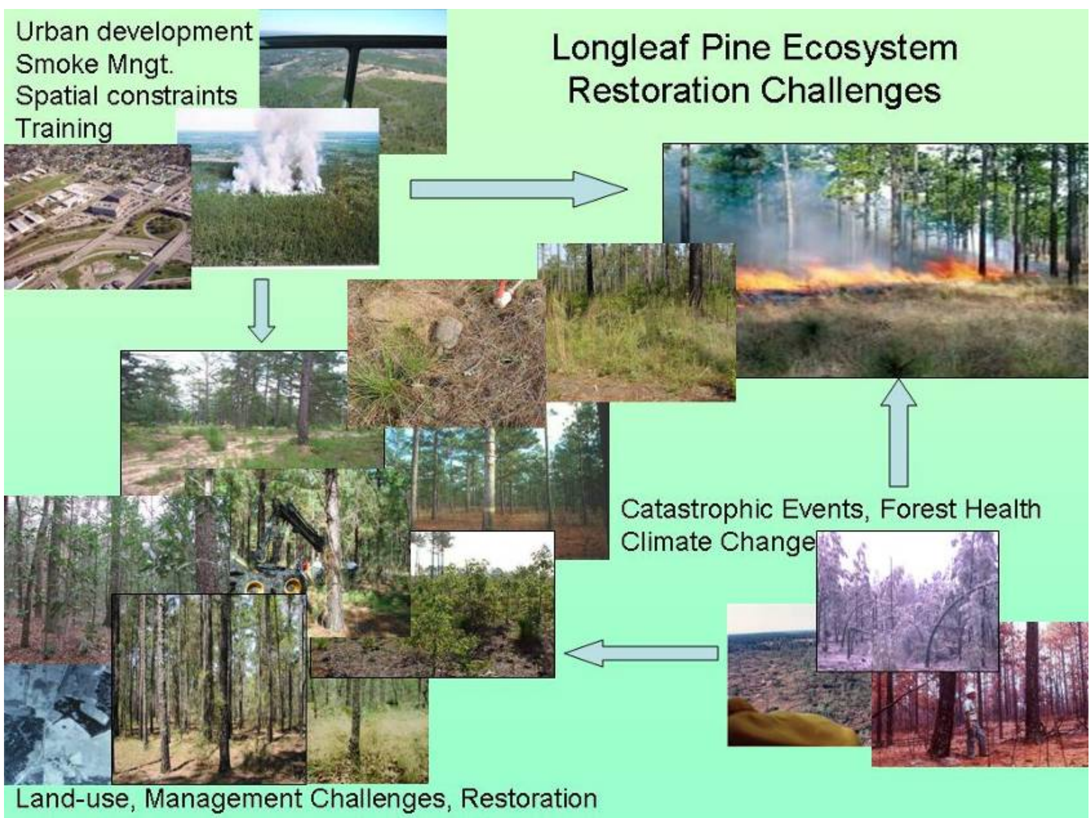
Ecosystem Management

Synthesis and Findings

Donald W. Imm, Hugh Westbury, Lee Mulkey, Rebecca R. Sharitz, Hal Balbach, Virginia Dale, Beverly Collins, Anthony Kryszik, Ramesh Reddy, Charles Garten, David Price, Graeme Lockaby, John DiLustro, William Goran

April 2009



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Synthesis and Findings

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Final Report

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Abstract: The SERDP Ecosystem Management Project (SEMP) was initiated in 1998 by the Strategic Environmental Research and Development Program (SERDP), after a 1997 workshop on Department of Defense ecosystem management challenges. After the workshop, SERDP allocated initial funding to a new project, titled the SERDP Ecosystem Management Project, designated as CS-1114, which changed in mid-2005 to SI-1114. SERDP funded five ecological studies under the guidance of SEMP (SERDP Ecosystem Management Project). Three of the studies focused on identify-ing ecological indicators that reflected training-caused disturbance. Two studies attempted to characterize state-transition thresholds that could be attributed to combined training and land management impacts. This report summarizes the findings and recommendations of these studies with regard to : (1) Potential Application, (2) Disturbance Threshold and Indicators, (3) Stream and Water Quality, and (4) Threatened, Endangered, and At-Risk species.

Executive Summary

Five ecological studies were funded by SERDP (Strategic Ecological Research and Development Program) under the guidance of SEMP (SERDP Ecosystem Management Project). Three of the studies focused on identifying ecological indicators that reflected training-caused disturbance. Two studies attempted to characterize state-transition thresholds that could be attributed to combined training and land management impacts.

Principal Findings

Water quality is directly related to physical and biological aspects of stream quality, and most influenced by total suspended sediments (TSS). Total suspended sediments, particularly those associated with storm flow, reduced the biological complexity, altered water chemistry, and reduced integrity of the stream systems. Further, these sediments influence water chemistry and the efficiency of chemical cycling through alteration of the organic matter cycling. Fine textured sediments are primarily derived from bank erosion, coarse-textured sediments from bed sediment instability.

Watershed-use directly influences water quality through its influence on hydrology and sediment movement. Hydrologic pattern, particularly the rapid increase of stream flow volume associated with storm events, greatly influenced stream quality, bed sediment stability, and transferred bed sediment volume. Watershed features that influence hydrologic pattern include: the percentage of shallowly sloped bare ground areas, road density, and frequency of stream crossings.

Training land flexibility, sustainability and suitability, as well as low cost maintenance are important attributes for the long-term military mission at Fort Benning. The potential to support a variety of training activities at necessary levels of intensity, duration, and frequency is directly associated with existing land condition, inherent topo-edaphic features, and land-use legacy. These attributes greatly influence the fragility and recoverability of sites. Further, marginally intact systems are slow to recover from additional disturbance of any type, including natural disturbance.

Productivity and sustainability are strongly influenced by carbon and nitrogen cycling patterns, process rates, and stocking forms. These factors are inherently influenced by natural soil characteristics and topography.

These factors can also be assessed using biological activity rates within the soil as well as microbial concentration and composition. The state and condition of the soil biota appear to be slow to change with recovery due to complex resource dynamics. In moderate to severely disturbed soil settings, the combined influence with other disturbances, including frequent fire, appears to slow soil-process recovery rates due to carbon limitation.

Several terrestrial biotic and abiotic indicators of land-use severity were identified and can be collectively used to interpret disturbance level. These indicators were particularly effective at representing “within state” changes such as the degradation of habitat quality, loss of ecological resilience and resistance to disturbance, etc. Particularly sensitive indicators include canopy characteristics, understory composition and associated life-forms as well as the collective pattern and influence of these features that characterize habitat quality for insects, songbirds, and other small vertebrates. Abiotic indicators include those that reflect atypical patterns of system dynamics (e.g., very low decomposition or N-fixation rates). Hence, “leaky” ecosystems that fail to conserve strongly conserved nutrients (e.g., N, P, etc.) are a strong indicator of declining system health, and a likely indicator of lost system resilience, sustainability, and flexibility to endure normal process changes. Unhealthy systems may also have elevated risk of forest health or invasive species problems.

Training-land disturbance at Fort Benning is collectively low with the majority of the upland area having minimal to moderate levels of legacy disturbance. These impacts and the capacity to recover is system dependent and may be influenced by upland legacy land-use. Therefore, our assessment is that collective remediation or restoration could still be fiscally achieved over a reasonable period of time. Most seriously disturbed areas are not likely to have the capacity of full recovery without significant rehabilitation investment. In contrast, most of the landscape is dominated by minimally to moderately impacted areas (e.g., forested to partially forested pine uplands). These areas remain at risk of serious degradation if additional training (e.g., BRAC) or new combinations of training are imposed without habitat amelioration that is focused on monitored findings. Most of the lowland and wetland areas are minimally impacted with the majority of the impacts being from legacy land-use (e.g., 19th /early 20th century agriculture), change in hydrologic pattern, and to a limited extent through the continued movement of sediments into the wetlands.

Fragmentation and off-post development around the boundary of Fort Benning (e.g., northern boundary) may lead to isolation of the current natural habitats. Such an event could influence watershed services that maintain appropriate hydrologic patterns and water quality. Further, isolation of these habitats could lead to greater regulatory expectations toward the regional environmental service responsibilities (e.g., RCW recovery) as well as regional conflicts in achieving those targets (e.g., RCW habitat burn requirements vs. air quality & smoke emission concerns).

General Findings and Potential Application

Baseline information concerning weather, soils, and water, as well as terrestrial and aquatic biota was collectively gathered by all studies using standardized techniques. This information has usefulness for management assessments, integrated multi-scale evaluations, and future research initiatives. GIS products include the development of a land-use map based on current and desired future conditions. These products can be used for RCW planning and T&E assessment as well as integrated future-use planning exercises.

Stream water collection stations and weather stations have been placed and maintained across the installation to give near-complete coverage. In addition to installation-wide usefulness, this information could be integrated with other state-wide and region-wide monitoring initiatives. Using the integrated information and GIS resources, the collective impact of training and management activities will be assessed using a watershed model (e.g., BASINS). Using baseline information, the program developed a means or approach for allowing rapid monitoring-based management response to sudden changes in near-future land-use initiatives.

Over time, the monitoring program has developed a means and protocol to coordinate and conduct ecological and biological research in a safe and effective manner. Though less than glamorous, avoidance of training conflict was critical for the continued existence and attraction of other additional research projects.

Disturbance Threshold and Indicators

Research developed a model to assess soil quality indicators and thresholds and their responsiveness to military training and forest management activities such as harvesting and prescribed burning. This information can be used to develop installation wide standards and guidelines to preserve ecosystem and forest health.

Collective research determined that a single indicator or threshold suitable for tracking the influence of all disturbances in all settings is unlikely to exist, but rather, a collective suite of indicators that define levels of disturbance. The most important factors include soil compaction, bare ground exposure, surface and sub-surface organic material, A-horizon characteristics, plant life-form assemblage, canopy conditions, ant community guilds, and rhizosphere activity rates. Most of these parameters can be periodically tracked without conflict with training activities. Now that standards are developed, these monitoring activities can be conducted at lower cost. Further efforts are needed to refine sampling strategies to best meet a balance between effective monitoring and limitations associated with cost, staffing, and access. These efforts should include cost-benefit analyses.

Stream and Water Quality

Through a series of relationships, stream concentrations of Total Suspended Solids (TSS) has been determined to elevate with increasing percentages of exposed soil area as well as the frequency and placement of trail and corridors. This information may allow for easy conversion from regulator-defined stream TSS standards to standards and guidelines concerning remediation strategies for exposed soil and road placement within a watershed.

The health of trees within the riparian zone is negatively impacted by small amounts of sedimentation from the upland. Much of the sedimentation is associated with runoff from unimproved roads. To track riparian recovery and continued forest health, these potential effects are now being tracked along a stream section of along a restored unimproved road.

Various stream features and indicators of stream health were determined to be within the range of accepted limits, therefore, factors such as dissolved oxygen (DO), conductivity, acidity, buffering capacity, and nitrate concentrations are not of concern to exceed standard limits.

Stream monitoring using the Rapid Bio-assessment Protocol resulted in modifications of interpretation to better represent the stream biota of Fort Benning streams. These changes will allow for a better representation of stream health conditions.

Threatened, Endangered, and At-Risk species

Forest management and light training activities did not appear to be direct threats to the gopher tortoise. Further, hormone levels did not strongly indicate stressed responses to translocations and upper-respiratory tract disease (URTD) was not found to be acutely lethal. Sandhill at-risk species occurrences were found to be related to locally variable soil and habitat conditions. The controlling features can be used to predict suitable conditions for many of the studied species. This information will provide for more efficient TERS surveys and could be implemented into restoration strategies.

Other Lessons Learned

Many ecologically-meaningful biogeochemical indicators were found to be inappropriate for monitoring because these parameters were proven to be: cost-ineffective, inappropriate to the scale of disturbance, high variance, difficult to interpret, extensive access or area required for effective sampling, or indirectly regulated by other uncontrolled factors. This knowledge can be used as a prototype for time and cost analysis during the development of future monitoring plans. The studies have collectively shown that training-related disturbance is unlikely to have a one-to-one relationship between questions and answers, but collective meanings are evident. This will fuel further refinement here and elsewhere by additional research and monitoring projects.

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Preface

This study was conducted for the Strategic Environmental Research and Development Program (SERDP) Office under SERDP Work Unit CS (later SI)-1114, “SERDP Ecosystem Management Program (SEMP).” The technical monitor at the time of the activities included in this report was Dr. Robert W. Holst, Program Manager. The Executive Director of SERDP is Mr. Bradley P. Smith.

The work was completed under the direction of the Ecological Processes Branch (CN-N) of the Installations Division (CN), Construction Engineering Research Laboratory (CERL), Engineer Research and Development Center (ERDC). The SEMP Project Director through August, 2005 was Mr. Bill Goran, who was succeeded by Mr. Lee Mulkey, of the University of Georgia. The CERL Principal Investigator was Dr. Harold E. Balbach. William Goran is the ERDC-CERL Strategic Program Planner. Alan B. Anderson is Chief, CEERD-CN-N, and John Bandy is Chief, CEERD-CN. The associated Technical Director was Dr. William D. Severinghaus, CEERD-CV-T. The Director of CERL was Dr. Ilker Adiguzel.

CERL is an element of the U.S. Army Engineer Research and Development Center (ERDC), U.S. Army Corps of Engineers. The Commander and Executive Director of ERDC is COL Gary E. Johnston, and the Director of ERDC is Dr. James R. Houston.

Acknowledgements

We first wish to thank the project PI's (Dale, Garten, Collins, Reddy, Kryszik), their staffs, and respective Universities and research institutions for their hard work and effort in completing their funded research projects. Their advice, access to data, and assistance in interpretation of results was invaluable. This also includes an unending list of SEMP project students, technicians, and scientists. We extend a special thank you to Virginia Dale for providing a consise, robust, well-evaluated integration report.

We also thank our host, Fort Benning, for continued fiscal, logististical, and infrastructure support; specifically, we thank John Brent, Pete Swiderek, Bob Larimore, Fred Weekley, Skip Caldwell, Johnny Markham, Theresa Davo, and their staffs. Without their cooperation, we would have not met our objectives. John and Pete continuously provided constructive commentary and behind the scenes support to improve the project. Lastly, we hope the staff accepts our apologies for repeated or silly questions that were derived from our own lack of understanding of their endless responsibilities and objectives.

We also appreciate the various reviewers in the development of these documents, most notably The Nature Conservancy as an organization, and as individuals. The Nature Conservancy allowed us full access to their products, data, and knowledge. These individuals have included Rob Addington, Tom Greene, Wade Harrison, John Hall, Maureen Mulligan, Catherine Prior, and Brant Slay. Discussions with Wade and John Doresky (USFWS) have kept the project relevant and applicable. Rob has provided timely review of various documents, initated integration, and thoughtfully discussed various aspects of the SEMP projects. Rob's ability to understand and appreciate the benefits and application of research, along with the usefulness of a scientific approach, provides unending value to Fort Benning.

We are thankful for the participation by numerous other Fort Benning research and monitoring groups that have provided invaluable assistance. A special thanks to Kathryn Madden (SREL) for providing various types of extended support to SEMP, we all are undoubtedly better people from knowing her and her joyful kindness. Michele Burton has happily, but unwittingly, served as the principal reviewer of this report. She has provided fresh scientific opinion and advice toward the SEMP integration with other studies and monitoring efforts, as well as the thankless job of reviewing SEMP repository data. Her efforts will insure that the SEMP initiative will continue to be available for use by Fort Benning staff.

We have greatly benefited from the administrative support provided by the Savannah River Ecology Laboratory and the University of Georgia. Our project leaders, Beverly Collins and Rebecca Sharitz, have provided scientific insight, integrity, guidance, and a never-ending willingness to support us and the SEMP initiative. John Dilustro deserves special thanks as the initial influsion coordinator, and for providing us with a stable starting point for SEMP integration. Our project manager, Lee Mulkey, provided leadership and a transition pathway that led to improved focus, identification of information gaps, and useful interpretation relative to other local to national initiatives. We also appreciate Lee's expertise, commitment, and friendship that led to improved project understanding, outlook, and communication by multiple benefactors, participants, and sources of funding. We wish to thank Hugh Westbury, who has played multiple scientific and administrative roles as well as provided project legacy and insight. Hugh has insured that equipment and vehicles were operational and available, he insured that researchers came back from the field unharmed (albeit sometimes frightened), he tended to the drudgery of paperwork and made the last-minute phonecalls to the right people, he always made sure that military missions were not compromised by field-going "bunny huggers," and most importantly, Hugh has been the friendly, smiling "host site" coordinator and has always been willing to help with projects.

We thank the ERDC-CERL staff such as Hal Balbach who has served as the COR for this project, and other research at Fort Benning. Hal provided charisma, friendship, credibility, coordination, scientific focus, and a broad-scope vision for the SEMP program. Hal insured progress was made, and support available to achieve purpose. Through his experience, Hal provided an unforeseen benefit as our "Wikepedia" of scientific and military information. Additionally, we thank Hal, Bill Goran, and Rose Kress (ERDC-EL) for their leadership and initiative in establishing SEMP, and helping to evolve the project within initial guidelines. We thank Chris Rewerts (CERL) and David Price (ERDC-EL) for help with making SEMP products available and more useful toward a broadened application; both were always available to collect and share data, review documents, and discuss the SEMP program.

We thank the SERDP office and program managers, Bradley Smith, Robert Holst, and John Hall. They have maintained a collective commitment to our project, as well as provided guidance and support toward the SEMP initiative. Our thanks extend to the various members of the TAC and SAB who have provided support, insight, and context to the projects over the years. We thank the SERDP office for their maintained commitment and tolerance, and occasional proding, even when we failed to meet certain deadlines or unwritten expectations.

Concluding, we are most thankful for support by our loving families and friends.

Unit Conversion Factors

Multiply	By	To Obtain
acres	4,046.873	square meters
cubic feet	0.02831685	cubic meters
cubic inches	1.6387064 E-05	cubic meters
cubic yards	0.7645549	cubic meters
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
Feet	0.3048	meters
hectares	1.0 E+04	square meters
horsepower (550 foot-pounds force per second)	745.6999	watts
inches	0.0254	meters
miles (U.S. statute)	1,609.347	meters
miles per hour	0.44704	meters per second
pounds (mass)	0.45359237	kilograms
square feet	0.09290304	square meters
square inches	6.4516 E-04	square meters
square miles	2.589998 E+06	square meters
square yards	0.8361274	square meters
yards	0.9144	meters

Part I: SEMP Program Review

1 Introduction to Fort Benning, GA

A setting for military training, conservation management, and ecologic study

Fort Benning is positioned within the Sandhill and upper Coastal Plain physiographic regions. The climate is characterized as being warm temperate with hot humid summers and cool mild winters. Mean summer temperature at Fort Benning is 27oC and a mean winter temperature of 9 °C; annual rainfall is 130 cm, with 53% falling from April through October (Lozar 2001, Mason 2002).

The mild humid climate favors the growth of bacteria and fungi, increases the rate of chemical reactions in the soil, results in rapid decomposition of organic matter, and facilitates the formation of soils low in organic matter and nitrogen and poor water holding capacity. Rapid cycling, high fixation rates (N, S), and high input from high NPP can quickly compensate for any potential loss of nutrients from fire (Christensen 1986, Kovacic et al. 1990, Hiers et al. 2003, Boring et al. 2004), particularly on sites without significant seasonal or annual moisture limitation.

The high precipitation leaches large amounts of nutrients and soluble bases and moves fine particles deep into the soil, resulting in acidic sandy soils low in fertility. Continuous leaching of the soil, along with the uptake of nearly all nitrogen results in low total nitrogen and an extremely high carbon/nitrogen (C/N) ratio (Vitousek 1982, Vitousek & Matson 1984). Several studies have suggested that P and K can limit productivity and influence community development when infrequent burning occurs or if sandy soils have been excessively used for agriculture (Cole & Rapp 1981, Gholz et al 1985).

The area is characterized by rolling hills that extend from elevations above 230 m to 55 m along the Chattahoochee River. Unlike the remainder of the Coastal Plain, the sandhill region has stream dendritic patterns that are reflective of higher gradient Appalachian plateau systems Besides influencing drainage patterns and habitat connectivity, patterns of stream dendrology also influence patterns of fire movement and dormant-season and growing-season burn frequencies.

The rolling uplands are underlain with sandy to sandy clay loams derived from in place weathering of sedimentary sandstones, mudstones, and conglomerates of the Tuscaloosa and Eutaw formations. The surface sands and loamy sands (tan, green) to sandy clay loams (blue) tend to be acidic and, at varying depths, underlain with less permeable sandy loam to clay loam sub-soils. Upland productivity is strongly dependent upon resource availability (water, nutrients) and storage capacity. Both of which are dependent upon activity rate and the amount of fine charged particles (clay, silt, organic matter) within the rooting zone. Because clay and silt are typically minor components of the soil profile, much of the holding capacity is dependent upon carbon cycle processes (including fire) that influence decomposition toward stable organic compounds (humus). Further, within and along the landscape, small changes in clay and silt particle contributions within the rooting zone do have significant influences on resource conditions. Past land-use influences carbon cycle rates and concentrations of forms.

The installation is in the Fall-Line Sandhills, the physiographic ecotone between the Coastal Plain and Piedmont in the Southeast, characterized by a gentle rolling topography and geological and ecological heterogeneity. There is also the intrusion of Loam Hills physiography from Alabama to further complicate the landscape. This biogeographical transition zone is characterized by high landscape and species richness, the occurrence of ecotonal taxa, and fire dependent taxa and plant communities. The Fall-Line Sandhills consists of deep porous sands deposited by the advance and retreat of early seas, with added soils and clays from erosion of the Piedmont. Erosion has resulted in a landscape of rolling hills. The soils formed in two types of parent material: marine sediments that have undergone considerable in situ weathering, and water-deposited material on stream terraces and floodplains (Trimble 1974, Herrick 2000, Shoenholtz et al. 2000). Paleudults are found on slopes where the upper sandy strata are thick, while Hapludults are found on thinner sand deposits underlain by more clayey materials.

Historically, the uplands are thought to have once been dominated by a matrix of longleaf pine associations that were intermingled with transitional pine-oak-hickory forests, both of which supported imbedded inclusions of upland hardwood forest, scrub barrens, and wetland seeps (Black et al. 2002, TNC, 1998, 2003). Due to complex topography that would have restricted fire movement, fire intervals were likely to have been 3-7 years, with some locales less frequently burnt. In certain areas, Native Americans may have accelerated burn frequencies, particularly near villages which were abundant along the Chattahoochee River. Several studies have suggested that the regional pre-settlement landscape consisted of longleaf-shortleaf-loblolly pines and southern mixed hardwoods forest communities, and was transitional to the longleaf pine – wiregrass or bluestem pyroclimax community further down the coastal plain where fire was more frequent and influential in structuring communities (Barnes et al. 1982, Monk et al. 1989, Peet and Allard 1993, Frost et al. 1993, Ware et al. 1993, Keys et al. 1999, Grossman et al. 2002, Imm & McLeod 2005, Peet 2006). Because of the transitional nature of the region, many past classifications have suggested a more significant landscape dominance of southern mixed hardwood, southern mixed pine-oak, and mixed pine systems (Quarterman & Keever 1961, Greller 1977, Daubenmire 1988, Vankat 1989). Other studies suggest nearly complete pine dominance at the time of European settlement (Sargent 1889, Harper 1919, Frost 1993).

Since European settlement, the natural fire regime has been altered in intensity, frequency, and seasonality. These changes have reduced the regulating effectiveness of fire and, coupled with other changes (e.g., early 20th century hunting pressure reduced deer and turkey populations which reduced acorn predation), has led to the development of mixed forests composed of relict pine and various hardwoods. These changes in canopy have been sufficient enough to alter nutrient dynamics, carbon cycling, productivity, composition, structure, forest microclimate, and habitat use as well as fuel loading and pattern that once supported natural fire movement. Today, across the southeast, a challenge exists in trying to redevelop the conditions to support the upland pine matrix.

Independent of the characteristics that once existed, it may be more important to focus on what is now potentially achievable. This assessment must consider the land-use legacies, expected-use and goals, and imbedded human-use patterns and restrictions associated with the surrounding area (Kane and Keeton 1998). Identifying the range of potential conditions (pasture, crop, hardwood forest, pine forest, etc.) and the capacity to achieve them without significant "gardening" is important when defining realistic stewardship goals and timelines.

From the standpoint of military use and training, the most flexible landscape setting is an openly forested park-like area that does not restrict visual contact between training groups. Therefore, densely forested areas or those with dense mid-stories are less preferred. Essentially, such a landscape setting is best created through periodic, low intensity fire that reduces seedlings, saplings, and shrubs and facilitates the development of near-complete grass dominated ground covers. These conditions can develop under pine or oak dominated canopies (pine savannas, oak barrens, oak woodlands, etc.); oddly enough, in some habitat settings, oak dominated systems may be better suited for training because of the capacity to vigorously sprout following disturbance and most have greater root volumes and deeper rooting profiles that are less impacted by compaction and more capable of restricting soil movement (Abrahamson et al. 1981, McGinty & Christy 1971, Drewa et al. 2002, Bond & Midgley 2001).

Currently, Fort Benning has an active three-year burn cycle, specifically addressing Red-Cockaded Woodpecker and longleaf pine management priorities. Fort Benning maintains the largest population of Red-Cockaded Woodpeckers in existence (Fort Benning, Integrated Natural Resources Management Plan). Ground cover is diverse consisting primarily of woody vegetation (tree seedlings, shrubs, and vines) along with perennial forbs and some grasses. Annual forbs are uncommon both in species and numbers. The shrub layer is poorly developed because of the frequent burn-cycle. Daunting challenges to land management and conservation upland forest efforts include questions such as: 1) after a maturing pine canopy has been thinned, how do you facilitate the natural reestablishment of native ground covers, 2) should healthy fire-tolerant, mature mixed canopied stands, that support native ground cover assemblages, be converted through replanting to longleaf pine whereby, mechanical and chemical site-prep and maintenance treatments may effect ground cover quality, 3) how do you retain the desired features that support RCW recovery within healthy or unhealthy mature pine stands, but still convert to the a stand dominated by longleaf pine, and 4) what is the most efficient and cost effective approach of improving the effectiveness of necessary prescribed burning without impacting military training or elevating air quality concerns.

Independent of site quality and military training needs, much of the upland landscape at Fort Benning is capable of supporting one of six primary states and has historic placement of each of these land-use types across the landscape, these include: non-agricultural urban- and rural-use (e.g., roads, housing, industry, landfills, other development), till agriculture (pivot center, row crop), non-row agriculture (e.g., pasture, hay, orchard, high yield livestock), yield-based forest production (e.g., coppice, pulp, saw, pine straw), multiple-use mixed forest (e.g., game management, unmanaged forest, upland hardwood), and historic longleaf pine landscapes with inclusions. Generally, these states contain various gradients of associated with form and function but can be ranked based on infrastructure development cost, maintenance cost, sustainability, suitability, productivity, etc. Further, conversion and transition matrices can be constructed to illustrate the transition feasibility and challenges that consider time and expenditure. These transitions and the likelihood of sustainable success in conversion are also strongly associated with the duration, extent, and influence of past land-use decisions. For the example the conversion from yield-based forest production to longleaf pine matrices is relatively low cost compared to conversion from a urban landscape, but likely to have similar time requirements.

Conversion costs associated with an area that has experienced multiple rotations of yield-based forest production are greater than those associated with a similar area that has had a single rotation of yield-based forest production. Finally, the historic artifacts of these states and conditions are now used for multiple types of mounted and dismounted training at different scales, intensities, durations, and frequencies. The combination of training types, with differences in land-use history and current conditions, as well as inherent soil and topographic gradients are likely to lead to differential response and sustainability across the current and historic training landscape.

Soils at Fort Benning have been heavily impacted by early settlement agriculture, extended periods of intensive agriculture, a long history of military training. These impacts coupled with undulating topography near the fall-line and soft parent material has resulted in significant change to soil characteristics including physical characteristics such as texture profiles and depths as well as bulk density. This has led to practical problems such as inaccuracy in classification, but functionally the disturbance impacts, military training atop of a landscape with a legacy of agricultural abuse, has led to increased ranges of conditions and greater local variability. For example, "Lakeland" soils (LaB, LaC, LaD) characterize broad xeric ridges and shoulders and have excessively drained profiles with a collective mineral horizon thickness of 165-200 cm of very sandy textured soils (NRCS, 1997), Troup soils (TrB, TrC, TrD) are better developed soils (Ultisols) associated with similar landscape settings as well as soil texture and profile characteristics. Generally, these soils have low variation within sites and moderately low variation between sites. However, at Fort Benning we found Lakeland soils to have as little as 6 cm depth to impermeable parent material, and nearly half of the sites to had depths to impermeable horizons of less than 80 cm. Further, these sites were highly variable (bulk density, texture, profile depths) at very local scales (30 m), and even more variable between sites (Sharitz et al., 2007). It is difficult to assess whether functioning processes and associated biota would be capable of optimizing the use, hence ecological capacitance and efficiency, of these sites with elevated variability.

Table 1. Depth to impermeable horizon for upland sandhill soils.

	LaB	LaC	LaD	TrB	TrC	TrD	VeC	Slope
0-10 cm	1	0	0	1	0	0	0	0
10-20 cm	3	0	0	0	0	0	0	0
20-40 cm	33	22	1	4	3	0	1	4
40-60 cm	40	52	5	16	16	13	1	6
60-80 cm	45	63	1	45	64	25	17	17
>80 cm	68	84	1	19	9	2	2	3

Assuming that such variance would still be within the range of the capacity of most natural systems, these observed patterns of variation are further expressed in biological conditions and biomass, as well as the dynamics of spatial processes (e.g., fire behavior). Further, it is unlikely these differences can be naturally mitigated within biological time scales; therefore, the existing patterns and associated variation are likely to continue to influence process rates and directions (e.g., broadened spatial and temporal variability in microbial activity).

Fort Benning wetlands have soils composed of alluvial silts, clays and loams along the river. Along streams, combinations of alluvial and colluvial sediments (sands to clay loams) as well as organic soils have developed. As with most locations in the Coastal Plain and Piedmont region, much of the hydrology, soils, and riparian vegetation have been drastically affected by post-European settlement land management activities (e.g., 19th century agriculture, reservoirs, etc.). Today's forests and riparian zones are generally composed of mixed hardwood and mixed pine-hardwood associations that harbor a diversity of understories. Wet to flooded areas support swamps composed of mixtures of bald cypress, tupeloes, red maple, and oak associations. Saturated areas tend to be dominated by mixed broadleaf evergreen associations (e.g., sweetbay-red bay).

Twenty-seven watershed management units are present at Fort Benning. These watershed units contribute to nine large streams that flow into the Chattahoochee River. In contrast with the Chattahoochee River, many streams at Fort Benning are classed as “blackwater” systems that are characterized by low suspended sediments, acidic chemistries, that have low nutrient content, low conductivity, and high levels of dissolved organic carbon that give the water a characteristic “tea color” appearance. Most blackwater streams are considered to have low productivity and high diversity with complex fish assemblages and high levels of benthic invertebrate species richness, with much of the benthic diversity attributed to midge fly (Chirionomids) species richness. Critical to benthic diversity is habitat complexity and the relative stability of the streambed, much of the habitat complexity can be attributed to amount and diversity of organic material as well as “run to riffle and pool” differences in bed sediment particle size. Again, past land-use has greatly affected stream habitat potential and associated habitat stability.

Extensive amounts of background and introductory material is available within the introductory and background sections of the various SEMP final reports. The INRMP (2001) also provides extensive information about the setting, history, land management objectives, as well as historic, current, and expected future impacts of military training. Further, an expanded GIS resource exists for Fort Benning as well as data repository web-sites that are accessible to the public.

Expectations and the reality of ecological indicators and thresholds

During the recent past and at a variety of scales, various research investigators, agencies, and organizations have proposed indicators and thresholds for monitoring of environmental change. In some cases, the proposed indicators focus on: (1) environmental restoration, remediation, and rehabilitation progress, (2) detection of unwanted or catastrophic change; (3) progress toward desired environmental conditions; (4) effectiveness of management actions, (5) meeting regulatory responsibility, and (6) detection of lost sustainability or efficiency of ecological services and land-use opportunities.

Results from indicator and threshold applications and studies are often criticized for one of the following reasons; (1) measurements are inappropriate to scale of concern, (2) insufficient information to represent the dynamics along a complete continuum, (3) indirect or constrained relationship with a disturbance, or (4) the variable is non-causal or deemed as correlative, indirect, or insignificant to top priority environmental issues. In the past, agencies have generally favored the use of indicator variables that are strongly associated with regulatory guidelines, while researchers have favored variables that are agglomerative, indicative of critical functions, or drivers associated with ecosystem dynamics.

Much of the SEMP research efforts, as well as other current research initiatives, have been focused on the latter setting as opposed to assessing the efficacy and fitness of using the former strategy (e.g., species indicators). Briefly, the problem with using species indicators is that the presence/absence or even abundance can be significantly affected by past local and regional dynamics (e.g., past land-use) as well as local stochastic influences (e.g., recent weather). Hence, conditions may be perfectly suited for an indicator species; therefore, perfectly meeting the conditions in which the species is to represent, but, the species may be absent. Obviously, the converse is true as well, persistence and existence of individuals of a indicator species in poorly suited areas; therefore, conditions that should be uninhabitable by the indicator, is often facilitated by combinations of chance, meta population dynamics (source-sink relationships), and biological inertia that reflects conditions of neighboring areas or past landscape settings.

For realistic reasons, most indicators and thresholds are focused toward evaluating disturbance as opposed to inherent, stochastic processes that influence sequence and direction of succession. When evaluating human-caused disturbance (e.g., training, development, land management, indirect, etc.) an appropriate definition of disturbance is something that results in a noticed and sustained shift in appearance and function for a definable period. Whereby, the definable period is that which exceeds some expectation to recovery. Usually, these periods are less than “within our lifetime” and geared towards reestablishment of a suite of potential uses. Functionally, different disturbances result in different types of change for different periods at different scales. Further, the natural landscape has a tendency to respond differently based on its inherent characteristics and inertia.

Scales appropriate for evaluating the impact of disturbance include; individual, population, community, ecosystem, landscape, and human land-use. At the individual scale, disturbance is something that results from a single or series of direct or indirect affects that result in or elevate the potential for a chronic or acute shift in functional efficiency, resource allocation, interaction with the environment, shift in the likelihood for survival, or shift at likelihood of reproductive success. At the population scale, "disturbance" begins to include factors or conditions that result in changes in the interaction of individuals, populations, and between species, changes in habitat quality and proportion, changes in pathways of dispersion, or changes in the dynamics of establishment.

Criteria that result in community or ecosystem change include factors that result in the change in stability and sustainability as well as criteria that define niche and habitat assembly, function pathways, efficiency in energy use and resource cycling, patterns of sustainable biodiversity, and ecosystem process rates. Lastly, landscape scale disturbances are those events that result in change of interactions of adjacent habitats and ecosystems that result in temporary or permanent shifts in the characteristics within the habitats and ecosystems as well as movement patterns of individuals and genetic material. From a human land-use perspective, a disturbance is something that changes the types of land-uses or diminishes the range of land management options and opportunities, or reduces the effectiveness and resilience of the landscape to support a land-use. Therefore, prior to identifying threshold criteria and indicators, some thought is needed to prioritize the scales of disturbance and features and conditions critical for tracking.

When used to detect unwanted or unexpected environmental change, ecological indicators and thresholds are expected to capture change that is outside the expected response to stochastic processes and normally functioning ecological drivers. The difficulty in identifying proper indicators, by its very nature, is that indicators and thresholds abound in and across ecosystems thus, are effectively "user-defined." The challenge is to define indicators that assess the general state of conditions at the installation level as well as identify those at the project or site level that could override or influence the pattern and state of conditions at broader scales. Of particular interest is the influence of disturbance on various aspects of biodiversity and habitat as well as the influence of degrading disturbance on general ecosystem function such related to productivity, chemical stability, and cycling within the ecosystem. Concerns over disturbance extend to direct and indirect effects associated with terrestrial and aquatic environments as well as the laws, policies, and directives designed to subjugate their protection and desired qualities.

Finally, most land managers are more comfortable with indicators and thresholds that are "conservative" by nature, whereby they slightly over-predict the possibility of a problem when none exists (false positive, Type I error), and under-predict the absence of a problem when one is present. Many program managers of "action-oriented" agencies (e.g., DOD, DOT) are encouraged to seek more appropriate balance of Type I and Type II error, and by design, other enforcement agencies (e.g., EPA, USFWS) tend to favor a more conservative balance. Emphasis on a conservative approach (reduced Type I error) also characterizes most of scientific studies. Many of these same studies would have been more informative if study designs were constructed to use power analysis, whereby the likelihood of Type I and Type II errors could have been equally explored..

The SERDP Ecosystem Management Project (SEMP) implemented three indicator studies and two threshold studies. The projects were initially uncoordinated, hence had limited opportunities for data integration. More recently, SEMP has been challenged with integrating the findings from these studies, and other relevant research, into management appropriate tools and recommendations. Finally, the initial projects were focused on sustainability as opposed to compliance, and did not emphasize any particular landscape (e.g., upland pine forest) or land management setting (e.g., desired future conditions). Therefore, the purpose of the integration was to refocus the results of the research and monitoring programs on complementing Integrated Natural Resource Management Plan (INRMP) and improving environmental management of Fort Benning with emphasis on target conditions. Ultimately, the lessons learned at Fort Benning may provide an example of how to improve environmental monitoring and management of DOD installations in general.

The primary use of SERDP-funded or outside research is in one of four areas: (1) the development or improvement of planning tools (e.g., pre-settlement forest vegetation GIS coverage, disturbed soil recovery model), (2) the development, improvement, and assessment of techniques for monitoring, (3) the identification, assessment, and evaluation of potential environmental risks (e.g., assessment of the potential impacts of tracked vehicles on gopher tortoises), and (4) to a lesser degree, the development of operational technologies for conservation and land management branch as well as training range management activities. More recent funding has favored studies that involve integrated use of multiple data sources to develop models at multiple scales and those that favor field demonstrations and application to develop adaptive management techniques. In addition to these studies, many on going studies designed to develop forecasting models continue to move forward.

2 Overview of Land Management, Conservation, and proposed Desired Future Conditions

The INRMP (Integrated Natural Resource Management Plan) is currently being revised, the proposed desired future conditions (DFC's) are focused on attributes of ecosystem condition, health, and sustainability as well as factors associated with the recovery of endangered species habitat and population status. Further, under written into some of these desired future conditions are regulatory guidelines and standards that are associated with land stewardship responsibilities as well as flexibility in land-use objectives (e.g., wildlife management). The identified opportunity areas and target objectives associated with each are as follows.

Longleaf pine ecosystem

A principal land management objective is to promote the re-establishment and improvement of a matrix of longleaf pine forest, woodland, and savanna associations. Whereby, a variety of ages, conditions, and settings are arranged across the landscape. Collectively, the system should be capable of supporting a wide range of species at multiple scales as well as capable of influencing the dynamics of other ecological systems at Fort Benning. The greatest challenge is conversion from other land uses to more appropriate conditions.

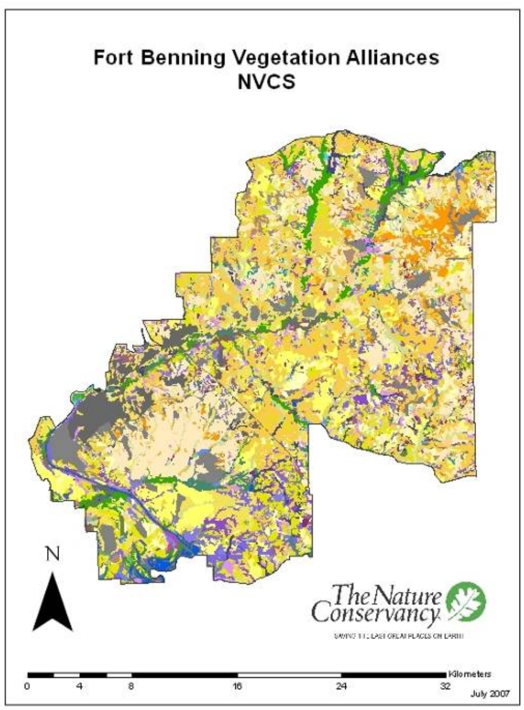


Figure 1. Fort Benning Vegetation Alliances.

These longleaf pine community alliances, and imbedded associations, should be dispersed across the landscape based on soil and topographic features as well as stochastic inherent fire response. Further, natural transitions will be encouraged between ecosystems, thus, providing habitat opportunities for transitional species.

The National Vegetation Classification System (NVCS) identified most of Fort Benning as being suited for a longleaf pine dominated alliances (tans, browns, etc.). Such classifications can be used as templates for restoration (Figure 2). Management decisions can be prioritized to facilitate the recovery of the system at landscape level.

Unlike many other communities and habitats associated with the southeastern Coastal Plain, the longleaf pine ecosystem creates a keystone condition that influences the processes and development associated with other adjacent habitats on the landscape. For example, many of the wetland communities (e.g., cane brakes) are thought to have been maintained by fires ignited in the more flammable pine savannas.

Beyond restoring community diversity, complexity, and efficacy, a straight forward goal is to advance toward a healthy, sustainable, naturally maintained, uneven-aged ecosystem. This process will require occasional controlled burning and low-impact silvicultural prescriptions to redirect the influence of undesired stochastic processes. These activities also have to be within the context of acceptable expense and best suited when projects "pay for themselves" through timber revenue.

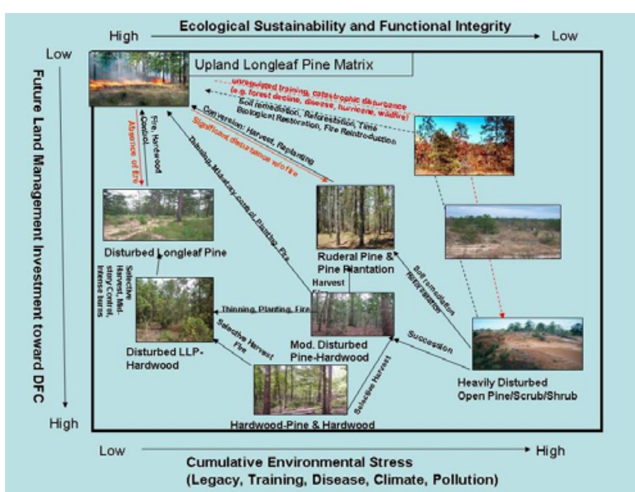


Figure 2. Ecological sustainability and functional integrity.

The creation and improvement of these habitats and their connectivity will proactively advance habitat development that is capable of supporting species of conservation concern such as the (F) red-cockaded woodpecker (*Picoides borealis*), (S) Bachman's sparrow (*Aimophila aestivalis*), (S) Henslow's sparrow (*Ammodramus henslowii*), coral snake (*Micrurus fulvius*), eastern diamondback rattlesnake (*Crotalus adamanteus*), fox squirrel (*Sciurus niger*), loggerhead shrike (*Lanius ludovicanus*), (S) gopher tortoise (*Gopherus polyphemus*), (S) southern hognose snake (*Heterodon simus*), (S) Gopher frog (*Rana capito*), (S) pine snake (*Pituophis melanoleucus*), and eastern milk snake (*Lampropeltis triangulum*). Rare plants include (S) trailing-bean (*Phaseolus polystachios*), lance-leaf wild-indigo (*Baptisia lanceolata*), split beard grass (*Gymnopogon brevifolius*), sessile tick-trefoil (*Desmodium sessilifolium*), big-pod wild-indigo (*Baptisia megacarpa*), (S) sandhill milk-pea (*Astragalus michauxii*), incised groovebur (*Agrimonia incisa*), (S) indian-olive (*Nestronia umbellata*), sandhills gay feather (*Liatris secunda*), pineland cress (*Warea cuneifolia*), and frostweed (*Helianthemum canadense*). Fort Benning state and federal listing information is based on available listings from GA DNR; (F) indicates federally listed species, (S) indicates state listed species, and unlabeled species are state-listed species.

Xeric barrens ecosystem

Another land management objective is to continue to facilitate the development and natural transition of xeric barrens and woodlands to the longleaf pine matrix ecosystem. Such habitats occupy deep, infertile, excessively drained xeric sands; whereby productivity is so low that sustainable longleaf pine savannas are unachievable. These systems support several endemic species of concern and due to limited past agriculture, harbor pine savanna endemics.

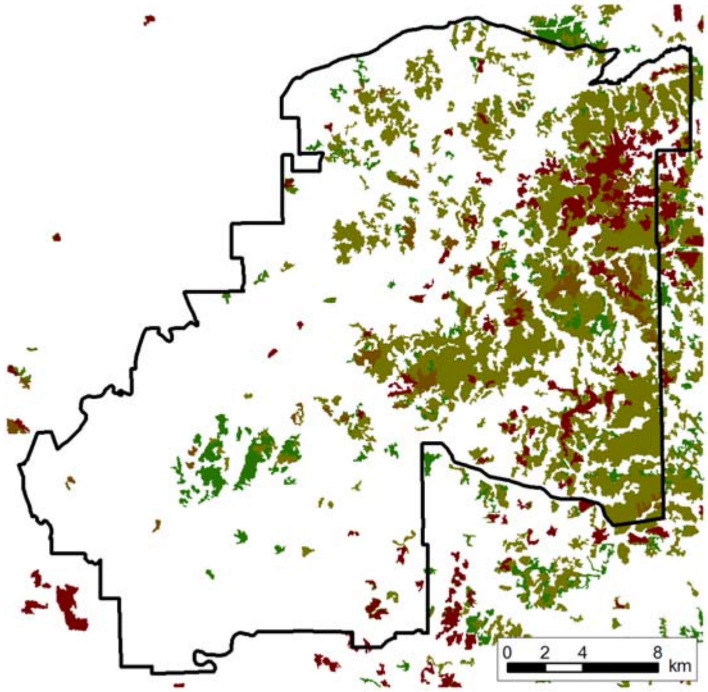


Figure 3. Potentially suitable areas for 5 commonly occurring dry savanna (green), woodlands (tans), and barrens (reds).

Figure 4. Open conditions in barren ecosystem.
adapted from Harper & Sharitz (2005).

Model-based figure 3 depicts potentially suitable areas for 5 commonly occurring dry savanna (green), woodlands (tans), and barrens (reds). All of these systems are within upland pine matrix system, but each occurs in slightly different landscape settings. Through limited harvest and occasional intense burning, barren ecosystems develop open conditions that provides habitat for a variety of unique species and state-listed species of conservation concern such as (S) gopher tortoise (*Gopherus polyphemus*), (S) southern hognose snake (*Heterodon simus*), (S) Gopher frog (*Rana capito*), (S) pine snake (*Pituophis melanoleucus*), (S) pickering's dawnflower (*Stylisma pickeringii*), woody goldenrod (*Chrysoma paucifolia*), (S) sandhill milkpea (*Astragalus michauxii*), sandhills gay feather (*Liatris secunda*), pineland cress (*Warea cuneifolia*), and (S) stonecrops (*Sedum neivii*, *Sedum pusillum*).

Slope and upland hardwood ecosystem

Based on soils and topography, about 10-12,000 acres are suited to support slope hardwood and pine-hardwood upland transition forests. These systems are composed of uneven-aged mixtures of upland hardwood and mixed pine-hardwood communities and generally associated with productive fine-textured upland soils, stream slopes, and steep ravines that grade upslope into upland longleaf pine forests and down-slope into mesic bottoms. Local species composition reflects edaphic conditions such as soil characteristics or topographic setting.

Overall management goals are to mange for mature, stable forest settings that minimize viability threats (e.g., invasive species, erosion) which could reduce functional effectiveness and integrity in regulating the transition of upland materials into wetland settings. Depending upon landscape position, periodic fire may occur. Harvesting will not be promoted, but may be used to adjust compositional trends, regulate invasive species, or convert toward a more appropriate and desired condition.

Most upland hardwood areas will be used to promote high-quality oak-hickory communities that are capable of providing sufficient mast for wildlife, including game populations. With wetland forests, these hardwood forests serve as near-continuous corridors for faunal and floral species movement as well as breeding sites for a wide variety of organisms. In part due to limited burning, these habitats are also important carbon and nutrient sinks; and with continued maturity, develop near permanently-stable forms of stored carbon (humus).

Figure 5. Upland hardwood ecosystem.

Though the habitat is generally limited in occurrence, within appropriate locales, upland hardwood and transition forest systems provide habitat for rare understory plant species such as (F) relict trillium (*Trillium reliquum*), (S) croomia (*Croomia pauciflora*), Flyr's nemesis (*Brickellia cordifolia*), (F) bottlebrush buckeye (*Aesculus parviflora*), incised groove-bur (*Agrimonia incisa*), (S) harpers heartleaf (*Hexastylis harperi*), American ginseng (*Panax quinquefolius*), bluets (*Oldenlandia boscii*), (S) plumleaf azalea (*Rhododendron prunifolium*), Arkansas oak (*Quercus arkansana*), dwarf chinkapin oak (*Quercus prinoides*), pale umbrella-wort (*Mirabilis albida*), broadleaf bunchflower (*Melanthium latifolium*), Carolina redtop (*Tridens carolinianus*), (S) Indian-olive (*Nestronia umbellata*), (F) dwarf sumac (*Rhus michauxii*), and bluehearts (*Buchnera americana*). Rare animals include eastern woodrat (*Neotoma floridana*), rafinisque's big-eared bat (*Corynorhinus rafinesquii*), southeastern myotis (*Myotis austroriparius*), wood thrush (*Hylocichla mustelina*), and Swainson's warbler (*Limnothlypis swainsonii*). These habitats, and associated riparian habitats, are critical breeding areas for many rapidly declining neotropical migratory songbird species (Audubon 2003, Partners in flight 2005) and harbor many uncommon Appalachian plant endemics that are less tolerant of burning and more demanding of cool microsite conditions.

Seepage bogs and depressional wetlands

Seepage bogs and depressional wetlands occupy, or could potentially occupy, a very small portion of the landscape but have a critical role in facilitating species richness and diversity at the landscape scale. Often neglected, these systems are best managed through selective harvest, erosion control measures, and increased fire frequency to promote and develop wooded, shrub, and herbaceous seepage bogs along wetland transitional areas of the longleaf pine matrix. Vegetation structure and composition should reflect local hydrology as well as edaphic and topographic characteristics that influence water drainage and storage. For example, some bogs are associated with

Figure 6. Seepage bogs and depressional wetlands.

streams while others are embedded within the longleaf pine ecosystem and contain fire-dependent herbaceous species.

Promote and improve habitat suitability for rare species or species of conservation concern such as the sweet pitcher plant (*Sarracenia rubra*), southern butterwort (*Pinguicula primuliflora*), tussock sedge (*Carex stricta*), horned-rush (*Rhynchospora scirpoides*), and shortleaf sneezeweed (*Helenium brevifolium*) are present. Seeps and depressional wetlands are also critical breeding habitat for a wide variety of amphibians and invertebrates; these including eastern tiger salamander (*Ambystoma tigrinum*), mole skink (*Eumeces egregious*), and gopher frog (*Rana capito*).

Fall line streams and bottoms

As pointed out by many studies and reviews, wetlands and riparian forests are a critical source of "ecological services." A short list that led to the wetlands protection act includes a) storm water regulation, b) storage and regulation of unwanted materials and compounds, and c) natural filtering, cleansing, and treatment of surface waters. Therefore, healthy wetlands and riparian corridors increase the likelihood that current and past Fort Benning land-use activities will maintain or enhance the water quality received by the Chattahoochee River.

Figure 7. Fall line bottom.

The stream and river bottom systems were greatly impacted prior to European settlement (Black et al. 2002, Dale et al. 2005) as well as by direct and indirect activities associated with settlement and development during the 19th and 20th centuries. The Chattahoochee drainage has been impacted by differential sedimentation, dam placement and flow regulation, changes in terrestrial land and water use, and lost forest continuity along the river and stream corridors. Since Fort Benning establishment, much less direct impacts have occurred; however, erosion from legacy disturbance and sediment movement continues to plague these systems.

Stream and river bottom communities will be passively managed as to allow for uneven aged competitive vegetation sorting that varies with edaphic conditions associated with topography, soils, and hydrologic patterns. This approach will allow for continued enhancement of natural sediment stabilization processes and continue to provide a buffer from terrestrial land-uses (e.g., tracked vehicle training). Further, allowing unmanaged forest succession to occur will allow species composition to adjust to post-European hydrologic and soil regimes.

A passive forest management approach will facilitate ecosystem advancement toward stable, sustainable, riparian forests that provide a buffer from upslope disturbances and restrict or reduce movement of soil and water-soluble chemical compounds into aquatic systems. This approach will also reduce the likelihood that currently present, but naturally controlled, invasive species (e.g., privet, tallow tree, Japanese knotgrass) will remain in check.

Figure 8. Fall line stream.

In some "at risk" areas, measures will be taken to stabilize stream banks and protect riparian zones. To further reduce threats to water quality and stream condition, road crossings will be restricted to "hardened" sections. Road densities will be reduced through revised transportation plans. Erosion control measures will be made to reduce non-point source pollution, increase bed-sediment and bank-sediment stability, as well as base-flow and storm-flow total suspended solid concentrations. Currently, concentrations of unwanted chemistries (e.g., nitrates, metals, etc.) are well within compliance standards; thus will not be an emphasized in the development of mitigation and control strategies.

Finally, the overall goal is to strive to manage the terrestrial and wetland habitats as to allow for native in-stream animal and plant diversity, and optimal water and stream quality conditions. These efforts will include efforts to achieve natural base- and storm-flow hydrology. Advancement toward this goal should increase habitat availability and suitability for riparian habitat improvement will increase habitat quality for rare riparian, bottomland, and wetland species such as such as swamp rabbit (*Sylvilagus aquaticus*), wood thrush (*Hylocichla mustelina*), Swainson's warbler (*Limnothlypis swainsonii*), (F) wood stork (*Mycteria americana*), (F) bald eagle (*Haliaeetus leucocephalus*), (S) swallow-tailed kite (*Elanoides forficatus*). These habitats also support herptofauna such as Florida green water-snake (*Nerodia floridana*), (S) Barbour's map turtle (*Graptymys barbouri*), (S) alligator snapping turtle (*Macroclemys temminckii*), (S) eastern milk snake (*Lampropeltis triangulum*), (S) eastern tiger salamander (*Ambrystoma tigrinum*), and (F) mole skink (*Eumeces egregious*).

Rare plants associated with these habitats include aquatic species such as (S) shoals spider-lily (*Hymenocallis coronaria*), (S) piedmont water-milfoil (*Myriophyllum laxum*); levee species such (S) georgia rockcress (*Arabis georgiana*); and bottomland and swamp species such as tussock sedge (*Carex stricta*), heartleaf tragia (*Tragia cordata*), trepocarpus (*Trepocarpus aethusae*), Nutmeg hickory (*Carya myristiformis*), broad-leaf marsh-st. johns-wort (*Tradenum tubulosum*), (S) sweet pitcher plant (*Sarracenia rubra*), drowned horned-rush (*Rhynchospora inundata*), Virginia thistle (*Circium virginianum*), Smith's sunflower (*Helianthus smithi*), and little-river black-eyed-susan (*Rudbeckia heliopsidis*).

Improvement and stabilization of wetlands and streams ultimately improves habitat for aquatic species such as several rare fish including bluestripe shiner (*Cyprinella callitaenia*), blacktip shiner (*Lythrurus atrapiculus*), (S) goldstripe darter (*Etheostoma parvipinne*), (S) broad-stripe shiner (*Pteronotropis euryzonus*), southern brook lamprey (*Ichthyomzon gagei*), (F) notchlip red-horse (*Moxostoma robustum*), and the occasional spawning (F) shortnose sturgeon (*Acipenser brevirostrum*). A large number of rare mussels are also associated with Fort Benning streams, these include; southern elktoe (*Alasmidonta triangulata*), delicate spike (*Elliotio arctata*), brother spike (*Elliptio fraterna*), winged spike (*Elliptio nigella*), inflated spike (*Elliptio purpurella*), (F) purple bank-climber (*Elliptoideus sloatianus*), lined pocket-book (*Lampsilis binominata*), (F) shiny-rayed pocket-book (*Lampsilis subangulata*), green floater (*Lasmigona subviridis*), (F) gulf moccasin-shell (*Medionidus penicillatus*), (F) oval pigtoe (*Pleurobema pyriforme*), sculptured pigtoe (*Quincuncina in-*

fucata), greater jumprock (*Scartomyzon lachneri*), and southern creek mussel (*Strophitus subvexus*).

Red-cockaded woodpecker

Figure 9. Red-Cockaded Woodpecker habitat.

A major management objective is to continue progress toward the recovery of the red-cockaded woodpecker (*Picoides borealis*) (RCW) population that is stable and sustainable, genetically diverse, and evenly distributed across the land-scape. The population may also include breeding clusters that are established on adjacent lands, and through source-sink relationships serve as sources for recolonization of nearby populations. Finally, an on going management objective is to pursue and develop effective management techniques that further reduce conflict with military training initiatives.

Gopher tortoise

Figure 10. Gopher tortoise.

Another management initiative is to facilitate the development of gopher tortoise (*Gopherus polyphemus*) populations that are composed of healthy individuals, and associated with stable numbers that are at or near carrying capacity for the habitat. As part of this initiative, facilitate the equitable distribution of active burrows across suitable soils with meaningful connectivity between burrow locations and habitat opportunities for commensal species. And as a mission related target, proactively manage the tortoise population for stable trends as to avoid future land-use conflicts with military training.

Relict trillium

Figure 11. Relict Trillium.

The principal management goal for relict trillium (*Trillium reliquum*) is to provide and encourage the development of habitat conditions that will allow relict trillium to expand and be capable of sustaining moderate disturbance associated with natural stochastic processes (e.g., treefall gaps). These actions will encourage, or actively invoke, the establishment of intermediate population locations as to allow for some genetic exchange between existing populations. Control invasive species (e.g., plants, fire ants), feral hogs, and other biological agents that could negatively affect trillium population size or health.

Programs to support attainment of desired future conditions

All programs within natural resources management will be aligned to attain the desired future conditions for focal conservation targets. Some specifics include:

- Timber management will continue to focus on silvicultural manipulations that favor species associated with mature and old-growth forest associations.
- Prescribed fire will be used to improve upland longleaf pine habitat condition, reduce the establishment of invasive species, and reduce insect pests.
- Soil erosion will be managed through physical road restructuring, contouring, placement of erosion control structures, and vegetation management to establish and maintain cover.
- Invasive species will be discouraged and/or eliminated through direct removal and reduced opportunities for establishment and expansion.
- Fort Benning habitats will continue to be managed to provide food and cover for desired game and non-game species.
- An integrated monitoring program will directly assess progress toward DFCs.

- Integrated, ecology-based models will be used to assess condition in areas with little or no available baseline information.
- Areas exhibiting unique compositional patterns (e.g., identified Unique Ecological Areas (UEA)) will have management plans that are tailored to enhancing unique qualities.
- Fish and game population health will be evaluated annually using accepted techniques associated with game harvest and population monitoring.
- Off-post conservation efforts will be guided to support attainment of DFCs on-post and also to advance regional conservation efforts.

3 Program Review of the SEMP Initiative

Background and program development of SEMP

SEMP was initiated as a result of the 1997 SERDP Ecosystem Workshop, which identified some of the critical knowledge gaps in understanding ecosystems; especially as they relate to military land management concerns. The primary themes that emerged from discussions included (1) ecosystem health or change indicators; (2) thresholds of disturbance; (3) biogeochemical cycles and processes; and (4) ecosystem processes as they relate to multiple temporal and spatial scales. The formation and application of the SEMP (SERDP Ecosystem Management Project) concepts began in 1999 (Figure 12), and were envisioned to integrate multiple-scale monitoring and research initiatives that were indicative of training-related ecological change and training-sensitive ecological thresholds between "desired" and "recovering" ecological states. SERDP Statements of Need were advertised based on the identified themes, and five projects were funded between 1999 and 2005. Much of the monitoring initiative was established and maintained through

Figure 12. "Old" SEMP 1999–2005 completed projects.

the ECMI program (Ecosystem Classification and Monitoring Initiative) that was directed by the ERDC-EL (Environmental Research and Design Center-Environmental Laboratory, Vicksburg, MS) and CERL (Construction Engineering Research Laboratory, Champlain, IL).

SEMP goals

The initial SEMP goals were to:

- establish one or more sites on DoD facilities for long-term ecosystem monitoring; and,
- pursue ecosystem research activities relevant to sustaining DoD mission capacity.

Then following technical and scientific review, SEMP goals were revised to become:

- at multiple scales (Figure 13), develop tools and techniques that permit installations to effectively and efficiently manage ecosystems that provide a sustainable and effective training environment,
- support attainment of environmental stewardship expectations, goals, and initiatives; and
- develop ecosystem-based scientific knowledge through research activities that are relevant to developing these management capabilities.

SEMP objectives

The SERDP Ecosystem Management Program's (SEMP) mission is to support the development of ecosystem science and technology to improve ecosystem management at military installations. Its goals since inception have been to:

- establish one or more sites on DoD facilities for long-term ecosystem monitoring, and,
- pursuit of ecosystem research activities relevant to sustaining DoD mission capabilities.

Over time, these objectives were further developed to include:

- conducting multiple ecosystem research and monitoring efforts relevant to the requirements of installations in across the southeastern United States,

- facilitating the integration of results and findings of research into DoD ecosystem management practices, and,
- Providing a platform for broader ecosystem research at Fort Benning.

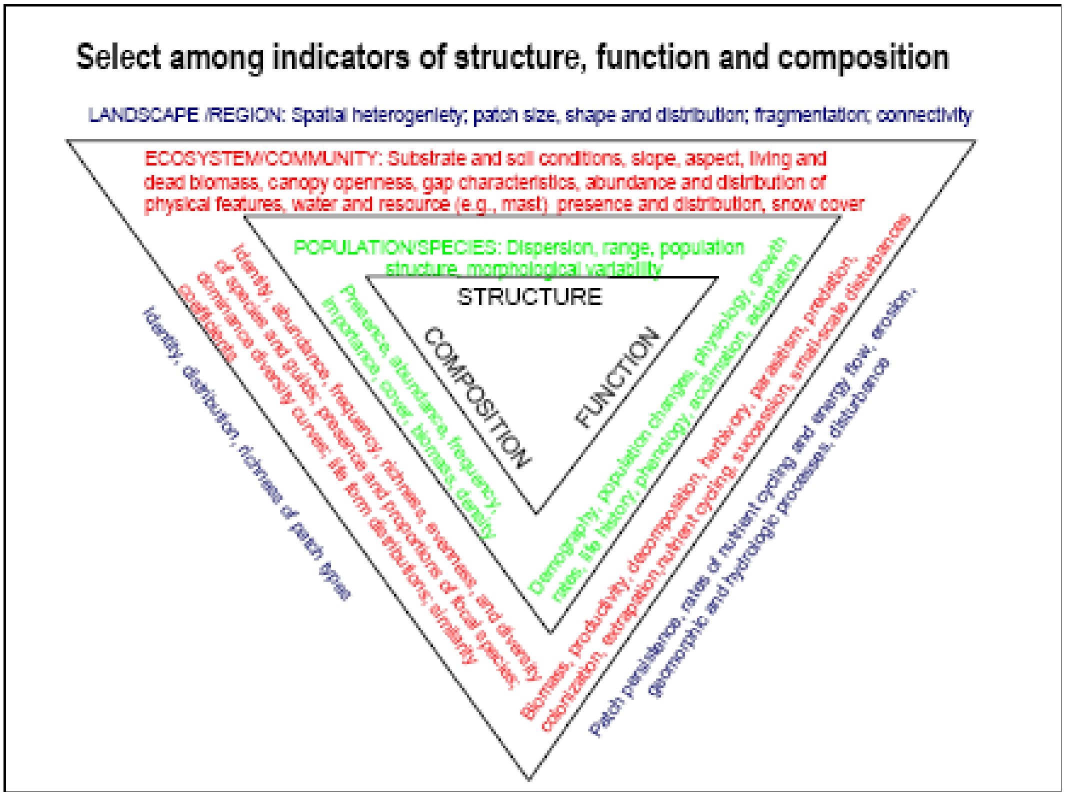
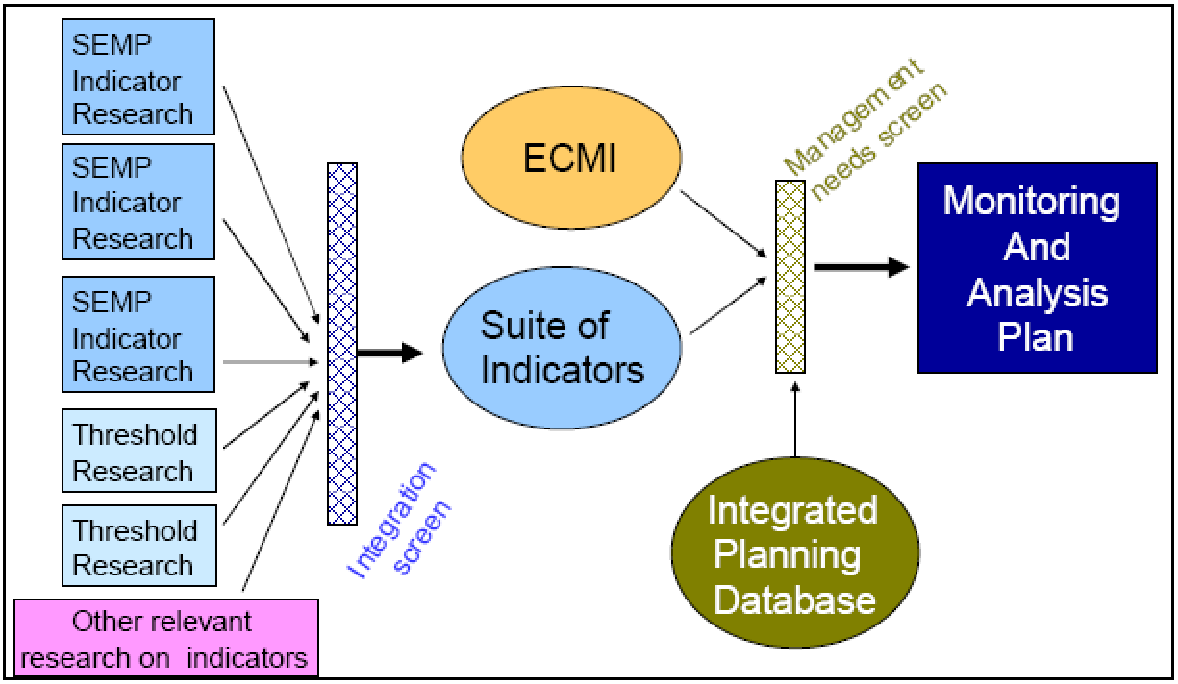


Figure 13. SEMP multiple scales develop tools and techniques that permit installations to effectively and efficiently manage ecosystems.

Expected benefits and application

Successful implementation of SEMP ensures maintenance and improvement of land sustainability and native biological diversity of terrestrial, freshwater, and marine ecosystems to support DoD military missions. The expected implementation strategy (Figure 14) is to convert relevant research findings into a suit of indicators that are associated with other data and then provide collectively be applied to provide monitoring guidance. Results from this project will provide a foundation for distinguishing negative impacts related to military training and testing activities from other sources of ecological variation and provide an improved knowledge base for evaluation of ecosystem health. Further, these techniques will also provide a means to periodically assess QA/QC issues related to land management and conservation activities.



Changes to the SEMP program

Though initially well reviewed and conceived, a series of problems associated with the SEMP program and projects were identified during the first five year period. In particular, the lack of coordination between projects was identified as a weakness and some questions arose relative to the appropriateness of the initiative relative to management priorities and realistic monitoring application.

Over time, in response to these concerns, SEMP has had a series of programmatic changes. Initially, the participating scientists identified and prioritized scientific needs. Many of these needs were focused on basic scientific principles or scientific inventory. Products were focused on developing peer-reviewed, scientific literature. The premise for expected application to land management and conservation initiatives was no different than application and consideration of other research findings.

The program has since evolved to allow for active participation of land managers in identifying and developing "statement of need" that reflect land management priorities and application. Greater emphasis is now placed on summarization reports that integrate and conceptually cross-tabulate concepts to application that can then be infused into land management planning or operations. The priority has since become applying the scientific findings to local host-site decision making with application to other land management institutions.

Many of these changes were developed through the action of SERDP staff as well as outside advisory and review committees. Based on recommendations from the science advisory board (SAB) and concurrence by the technical advisory committee (TAC), a program review was conducted and resulted in a RAND report as well as a series of workshops to facilitate program improvement (Fort Benning needs session, SEMP Strategic Planning Workshop, Partners along the Fall-line workshop, etc.). The RAND report recommendations include:

- improve strategic planning,
- increase relevance of research to host installation management needs,
- improve application and integration of SEMP data to support other studies,
- increase QA/QC associated with analysis and study design,
- develop a revised and broadened process for project scope and means of funding,
- centralize communication associated with SEMP planning, methods, & product development,
- improve SEMP program management and administration, and,
- improve and refine the TAC functioning.

The Fort Benning management staff as well as reviewing committees concurred with the RAND report findings and help refine the suggested changes that would increase application of scientific findings concurs that SEMP should continue for another phase (e.g., 5 more years). Potential results and expertise gained from continued SEMP research investment should help the installation in the following areas:

- Linkage with the Integrated Natural Resources Management Plans (INRMP),
- Installation sustainability planning and monitoring at various scales,
- Red-Cockaded Woodpecker (RCW) recovery efforts,
- Longleaf pine matrix habitat assessment and restoration, and
- Development of land-management decision-making tools.

In addition to support of these program initiatives other expected needs were forecasted. Through the SEMP strategic workshop, the Fort Benning staff and workshop participants identified two general focus areas and a short list of imbedded issues represent current management concerns. The focus areas include:

- Sustainable Watersheds
- Establish, develop, and apply watershed assessment capabilities such as:
- A means to understand and measure capacity for use and its relationship with water and stream quality,
- An integrated predictive model that addresses regulatory concerns with emphasis on the impacts of training and land management actions.
- Improve management capabilities to measure and interpret cross-boundary influences on watershed processes, hydrology, and water quality conditions.

- Establish, develop, and improve tools and techniques associated with assessment of multiple disturbances (e.g., DMPRC, BRAC, etc.) on water and stream quality.

Sustainable forest habitats

Evaluate concerns over forest decline and long term habitat preservation,

Develop sustainable forest practices,

Develop integrated initiatives focused on species and regional habitat concerns.

Facilitate the development of appropriate habitats across the landscape in proportions that reflects need and sustainable capacity.

"New" SEMP Associated Projects

- Funded as separate projects within SI area
- Managed completely by the proposing PI
- May involve study sites other than Ft. Benning
- SEMP assists with data sources and host-site logistics
- SEMP uses project findings for host-site tech transfer

SI-1186
Riparian Ecosystem Management at Military Installations: Determination of Impacts and Restoration and Enhancement Strategies
Dr. Patrick J. Mulholland

SI-1302
Impacts of Military Training and Land Management on Threatened and Endangered Species in the Southeastern Fall Line/Sandhills Comn
Dr. Rebecca Sharitz

SI-1303
Regenerating Longleaf Pine on Hydric Soils: Short- and Long-Term Effects on Native Ground-Layer Vegetation
Dr. Joan Walker

SI-1462
Developing a Spatially Distributed Terrestrial Biogeochemical Cycle Modeling System to Support the Management of Ft. Benning and its Surrounding Areas
Dr. Shuguang Liu

SI-1547
Development of a Watershed Modeling System for Fort Benning Using the USEPA BASINS Framework (FY07 New Start)
Anthony Donigan, Jr.

Figure 14. "New SEMP Associated projects.

Following the identification of these issues and approaches, the current SEMP program has the following objectives:

- provide a capacity for the infusion of technologies and research findings into land manager planning and operations,
- develop monitoring recommendations and priorities for an installation-wide monitoring program,
- serve as a conduit to provide scientific topic assessments and summaries related to current management concerns,
- support and coordinate of ongoing studies,
- integrate scientific information from past and ongoing SERDP- and non-SERDP funded studies,
- develop, implement, and oversee adaptive management projects, and,
- assist in identifying future research needs that are applicable to the host-institution as well as regional concerns.

Ecosystem characterization and monitoring initiative

Journal articles

Published

Jackson, S. and Bourne, S. 2005. Using feature extraction to monitor urban encroachment. Earth Observation Magazine. 14(2):26-29.

Lee, A., R. Kelly, and R. Kress. 2005. The use of Rapid Bioassessment Protocols (RBP) in long-term monitoring. Federal Facilities Environmental Journal/Spring 2005. Published on-line in Wiley Interscience (www.interscience.wiley.com) DOI:10.1002/ffej.20045

Accepted/in press

Guilfoyle, M., S. Anderson, and S. Bourne. Trends in habitat fragmentation and forest birds at Fort Benning, GA. The Southeastern Naturalist. (Accepted)

Technical reports

Published

Bourne, S.G., and M.R. Graves. 2001. Classification of land-cover types for the Fort Benning ecoregion using Enhanced Thematic Mapper (ETM) data. ERDC/EL TN-ECMI-01-01. U.S. Army Engineer Research and Development Center, Environmental Laboratory, Vicksburg, MS.

Graves, M.R. 2001. Watershed boundaries and relationship between stream order and watershed morphology at Fort Benning, Georgia. ERDC/EL TR-01-23. U.S. Army Engineer Research and Development Center, Environmental Laboratory, Vicksburg, MS.

Graves, M.R., and S.G. Bourne. 2002. Landscape pattern metrics at Fort Benning, Georgia. ERDC/EL TN-ECMI-02-2. U.S. Army Engineer Research and Development Center, Environmental Laboratory, Vicksburg, MS.

Hahn, C.D. 2002. Evaluation of ECMI instrumentation deployed at Fort Benning. ERDC/EL TN-ECMI-02-1. U.S. Army Engineer Research and Development Center, Environmental Laboratory, Vicksburg, MS.

Hahn, C.D. 2001. Ground control survey at Fort Benning, Georgia. ERDC/EL TN-ECMI-01-02. U.S. Army Engineer Research and Development Center, Environmental Laboratory, Vicksburg, MS.

Hahn, C.D., M.R. Graves, and D.L. Price. 2001. S-Tracker survey of sites for long-term erosion/deposition monitoring. ERDC/EL TR-01-18. U.S. Army Engineer Research and Development Center, Environmental Laboratory, Vicksburg, MS.

Hahn, C.D., and D.L. Leese. 2002. Environmental data collection at Fort Benning, Georgia, from May 1999 to July 2001. ERDC TR-02-3. U.S. Army Engineer Research and Development Center, Environmental Laboratory, Vicksburg, MS.

Jackson S.S., and S.G. Bourne. 2004. An automated procedure to monitor urban encroachment over time on Fort Benning military installation. ERDC/EL TN ECMI-04-01, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Kress, M.R. 2001. Long-term monitoring program, Fort Benning, GA; Ecosystem Characterization and Monitoring Initiative, version 2.1. ERDC/EL TR-01-15. U.S. Army Engineer Research and Development Center, Environmental Laboratory, Vicksburg, MS.

Leese, D. (2005). Resources, Equipment and Logistics in Support of Long-term Monitoring at Fort Benning. ERDC/EL TN-ECMI-05-2 <elpubs/pdf/ecmi0502.pdf>, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Submitted

Lord, E. and S. Bourne. SEMP Data Repository Users Manual. ERDC/EL SR XX-XX, U.S. Army Engineer Research and Development Center, Vicksburg, MS. (Submitted September 2004)

Overall SERDP Ecosystem Management Project

Technical reports

Published

Balbach, H.E., W.D. Goran, T. Aden, D.L. Price, M.R. Kress, W.F. DeBusk, A.J. Krzysik, V.H. Dale, C. Garten, Jr., and B. Collins. 2001. Strategic Environmental Research and Development Program (SERDP) Ecosystem Management Project (SEMP) FY00 annual report. ERDC SR-01-3. U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory, Champaign, IL.

Balbach, H.E., W.D. Goran, T. Aden, D.L. Price, M.R. Kress, W.F. DeBusk, A.J. Krzysik, V.H. Dale, C. Garten, Jr., and B. Collins. 2002. Strategic Environmental Research and Development Program (SERDP) Ecosystem Management Project (SEMP) FY01 annual report. ERDC SR-02-2. U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory, Champaign, IL.

Balbach, H.E. and E.L. Keane. March 2007. Strategic Environmental Research and Development Program (SERDP) Ecosystem Management Project (SEMP) 2005 Annual Report. ERDD-SR-07-2. U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory, Champaign, IL.

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Goran, W.D., T. Aden, H.E. Balbach, B. Collins, V. Dale, T. Davo, P.J. Guertin, J. Hall, R. Kress, D. Price, and P. Swiderek. 2002. The SEMP approach: plans and progress of the Strategic Environmental Research and Development Program (SERDP) Ecosystem Management Project (SEMP). ERDC SR-02-1. U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory, Champaign, IL.

Goran, W.D. 2004. SERDP Ecosystem Management Project (SEMP) 2003 technical report. ERDC SR-04-3. U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory, Champaign, IL.

Goran, W.D. 2004. SERDP Ecosystem Management Project (SEMP) 2003 administrative report. ERDC SR-04-4. U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory, Champaign, IL.

Goran, W. D. and H.E. Balbach. June 2006. SERDP Ecosystem Management Project (SEMP) 2004 administrative report. ERDC SR-06-1. U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory, Champaign, IL.

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Lozar, R.C., and H.E. Balbach. 2002. NASA MODIS products for military land monitoring and management. ERDC/CERL TR-02-31. U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory, Champaign, IL.

Lozar, R.C., H.E. Balbach, W.D. Goran, and B. Collins. 2002. Proceedings of the "Partners Along The Fall Line: Sandhills Ecology and Ecosystem Management Workshop." ERDC/CERL SR-02-2. U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory, Champaign, IL.

4 An Overview of SEMP Research Project Findings

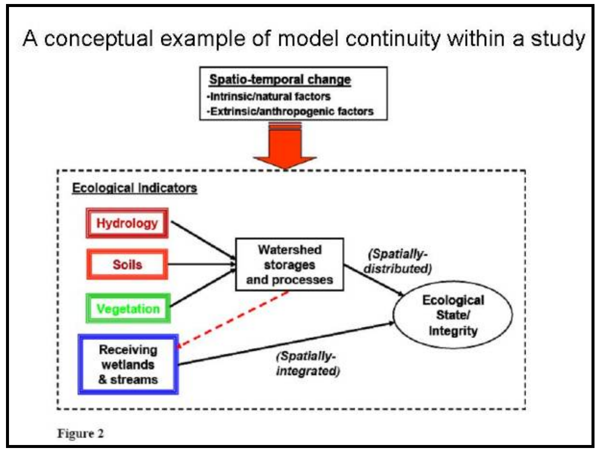

Figure 15. A conceptual example of model continuity within a study.

The following text sections are modifications of extracted sections of project final reports. Some commentary and reference to outside studies has been added for point clarification. In some cases, sections have been revised, shortened, or modified to improve consistency with other final report sections. Further information that yielded these conclusions are provided within the relevant final reports for each project. The figures used are directly extracted from sections of the respective final reports and referenced back to their original source, section, and page. Following each of these sections, an author summarization and comparison is provided.

SEMP Project CS-1114A-99: Determination of indicators of ecological change (PI: R. Reddy, Univ. of Florida)

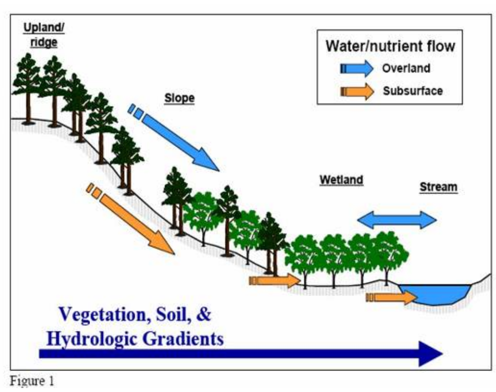

Figure 16. Vegetation, soil, and hydrologic gradiants.

The goal of this project was to measure various indices associated with vegetation, soils, and hydrology; then develop a spatially-integrated dynamic process model (Figure 16). In doing so, statistically identify critical factors (indicators) that reflected ecosystem integrity and ecological response to natural and human disturbance. The initial foci were parameters associated with the relationship between vegetation, soil quality, hydrologic attributes, and stream water and habitat quality. Dynamic models based on field observations were developed for each model component then nested using a spatially-explicit structured equation model. The outputs were then associated with observed qualitative conditions that reflect ecological state and system integrity (Figure 17). In general, differences were greatest between intermediate and severely disturbed training areas. These differences reflect state changes as well as shifts from biological regulatory pathways to abiotic control.

Overall findings and accomplishments

Severe impacts to soil, vegetation, and hydrologic processes are associated with mechanized training involving tracked vehicles. Moderate to severe impacts also occurred in areas of non-military land use, primarily due to forest clear-cutting activities. Hydrologic and ecological impacts observed in wetlands and streams down slope from clear-cut upland areas had characteristics similar to those observed in areas associated with severe military disturbance; however, since land management activities are typically have shorter durations, the extent and severity of these disturbances are less and recovery more rapid than those associated with mechanized military activity. The soil, vegetation and hydrologic parameters (potential indicators) that were most closely correlated with predetermined site disturbance levels (low, moderate, severe) were those that reflected loss of vegetation biomass and community structure, disruption and/or compaction of soil, loss of soil A horizon (Figure 18), and soil organic matter in uplands; and accelerated sedimentation of clay and sand in wetlands. In wetland areas, those down slope from impacted uplands, the relationships between soil biogeochemical indicators and upland impacts were less clearly defined. However, indicators that directly related to wet-

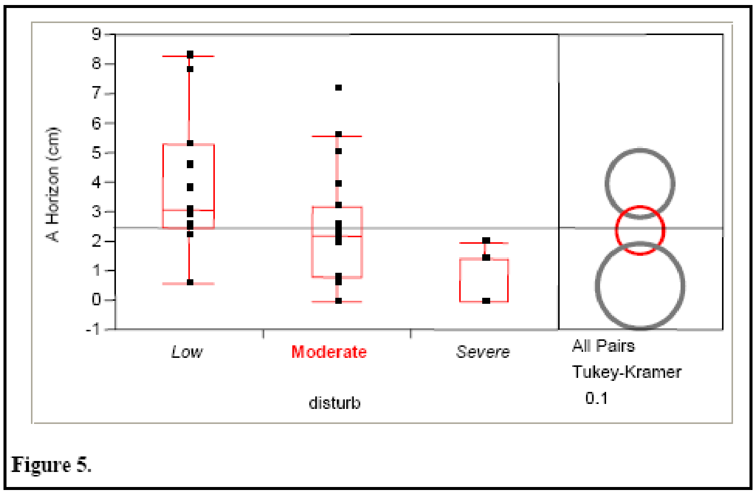

Figure 17. Severity of impacts to soil, vegetation, and hydrologic processes.

land soil organic matter content (and "dilution" by clay or sand) were useful in identifying sediment-impacted wetlands located below severely-disturbed upland areas. The potential value of wetland soil biogeochemical properties as indicators of nutrient loading in uplands (e.g., from excessive fertilization or waste disposal) was not realized at the Fort Benning study areas, due to the nature of the ecological impacts in upland areas.

Soil biogeochemistry

Consistent with other SEMP studies, thickness of the A horizon is an indicator of soil disturbance resulting from loss of topsoil (erosion) or mixing of A and E horizons. A-horizon depths decreased with increased level of disturbance category: bottomland sand-loam, Low to Medium; upland clay, Medium to High; upland sand, Low to Medium to High. A-horizon loss results in decreased nutrient and water storage capacity as well as rhizosphere activity.

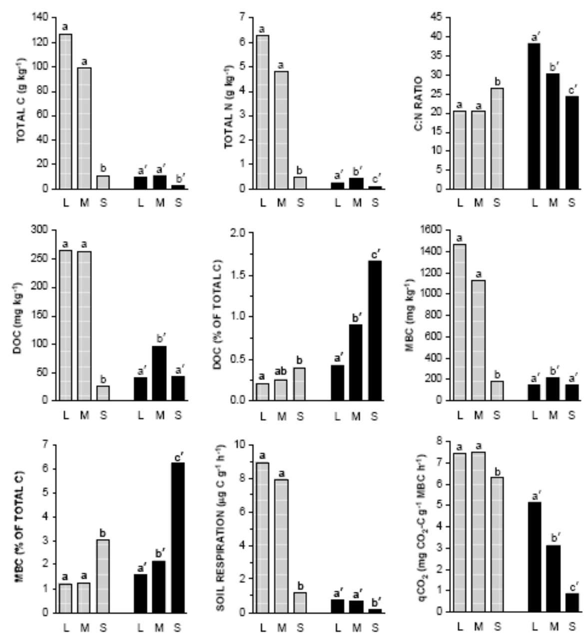

Figure 3
Summary results for the Fort Benning Phase 2 soil characterization study. Data points represent mean values for each level of site impact (L = low, M = moderate, S = severe) for bottomland (hatched bars) and upland (solid bars) sites. Means followed by the same letter are not significantly different ($P<=0.05$); separate means comparisons were performed for bottomland and upland sites.

Figure 18. Summary results for the fort Benning Phase 2 soil characterization study.

Biogeochemical cycling in soils and vegetation are greatly influenced by soil-water content, which is influenced by landscape position, land-use history, and soil characteristics. Soil organic matter, and its cycling, is also an important biogeochemical indicator that regulates mineralization process rates and greatly influences storage capacity of available and unavailable nutrient forms.

Total organic C is an indicator of soil disturbance resulting from loss of topsoil (erosion) or mixing of A and E horizons (Figure 19). Anthropogenic impacts on soil and ground cover in upland areas of the Fort Benning study site included (1) disturbance or destruction of vegetation, resulting in increased area of bare ground and a greater proportion of early successional species, (2) disruption of soil A horizon and effective burial or dilution of biologically-active topsoil with organic-poor lower horizons, (3) increased erosion in uplands and deposition of sediment in bottomland areas, and (4) loss of soil A horizon in severely-impacted upland areas. Impacts to bottomland soils were primarily associated with soil disturbance in adjacent upland areas (Table 2), and typically involved accelerated deposition of clay and silt (moderately-impacted areas) or sand (severely-impacted areas). The primary impact of increased sedimentation, with regard to soil C and N dynamics, was dilution and/or burial of organic matter contained in the native wetland soils. For upland and bottomland sites, the observed decrease in soil Total Carbon (TC) and Total Nitrogen (TN) with increasing level of impact was indicative of the reduction in soil organic matter content of surface horizons.

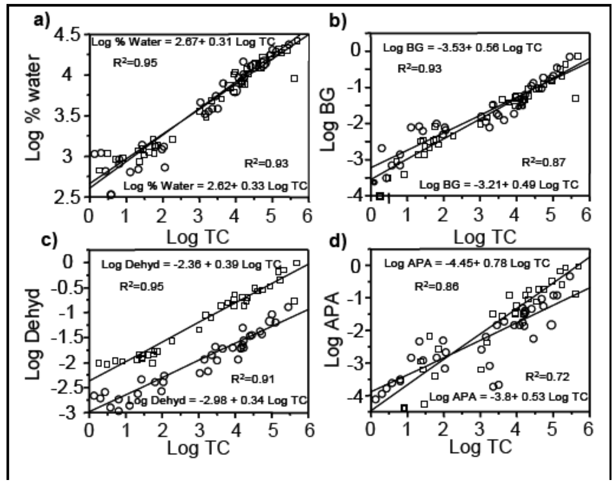

Figure 19. Relationship between the log TC values and (a) log percent soil moisture; (b) β-glucosidase activity; (c) dehydrogenase activity; and (d) acid phosphatase activity.

Assuming microbial saturation and sustained process efficiency, microbial biomass (as C) is an indicator of the size of the labile (readily available for biological uptake) soil C pool (Figure 19). Microbial biomass Carbon (MBC) and soil respiration showed a significant decrease with increasing site impact, consistent with the trend observed for TC. However, changes in MBC with impact level were not directly proportional to changes in TC, as demonstrated by the significant increase in MBC:TC with site impact. Interpretation of this finding is difficult.

Table 2. Summary comparison (mean 10th percentil and 90th percentile values) of soil chemical properties among bottomland, mid-slope, and upland/ridge sites in the Fort Benning study area.

	Bottomland (n=98)			Mid-Slope (n=101)			Upland/Ridge (n=101)		
	Mean	10th pct	90th pct	Mean	10th pct	90th pct	Mean	10th pct	90th pct
pH	4.99	4.19	5.85	5.30	4.71	5.85	5.26	4.76	5.71
Total C (g kg^{-1})	38.3	7.0	100.6	11.8	6.5	18.7	10.0	3.5	18.5
DOC (mg kg^{-1})	121.3	21.3	272.7	70.8	20.2	135.3	60.1	15.8	151.3
MBC (mg kg^{-1})	561.2	122.0	1435.0	232.3	79.0	425.2	205.2	64.9	372.7
Total N (g kg^{-1})	2.03	0.33	4.92	0.45	0.23	0.75	0.39	0.17	0.67
Exchange. NH4-N (mg kg^{-1})	10.70	2.00	22.40	4.30	1.20	7.70	5.00	1.10	9.60
Total P (mg kg^{-1})	200.8	59.5	435.5	80.3	42.9	124.8	79.7	39.3	137.8
Mehlich-P (mg kg^{-1})	1.32	0.35	1.81	1.20	0.54	1.93	2.09	0.48	3.60
Mehlich-Fe (mg kg^{-1})	306.0	35.1	722.6	40.0	17.7	64.1	34.1	13.3	57.6
Mehlich-Al (mg kg^{-1})	603.1	94.6	1444.7	258.0	108.1	414.1	233.3	113.0	354.8
Mehlich-Ca (mg kg^{-1})	232.3	21.1	534.7	220.5	15.7	666.3	166.7	11.6	626.4
Mehlich-Mg (mg kg^{-1})	66.4	11.8	185.4	79.5	2.6	268.7	64.6	2.5	301.7

Soil (microbial) respiration appears to be an indicator of the amount of activity rates as well as bio-available soil C. Soil respiration rate was roughly correlated with TC concentration, as would be expected since organic C provides the metabolic substrate for soil microorganisms. Since soil respiration was determined by laboratory incubation of soil samples at a constant temperature, the measured rates represented (1) primarily microbial respiration rather than root respiration, and (2) potential respiration rates rather than actual in situ rates at the time of sampling. Therefore, soil respiration rates reported in this study were indicatory of the size of the bio-available pool of soil C.

Overall, ratios of microbial biomass:organic C and respiration:biomass are indicative of bioavailability of the soil organic C pool. Metabolic quotient (qCO2), or specific respiration rate (normalized to MBC), showed a significant decrease with increasing level of impact. In this study, it was apparent that decreasing qCO2 with increasing site impact was related to substrate bioavailability, and was not a response to environmental (external) stress. Although the biochemical processes governing the relationship between qCO2 and soil impact or condition are not known with any certainty, our study results suggest that this parameter may be a useful indicator of ecological condition or change, primarily for upland areas. The ratio of microbial biomass C to soil organic C, a.k.a. microbial quotient, has been related to soil C availability and the tendency for a soil to accumulate organic matter. Based on combined results of Phases 1 and 2 of this study, both DOC:TC and MBC:TC were found to be relatively good indicators of soil “quality” in upland areas, as related to site impacts or ecological condition.

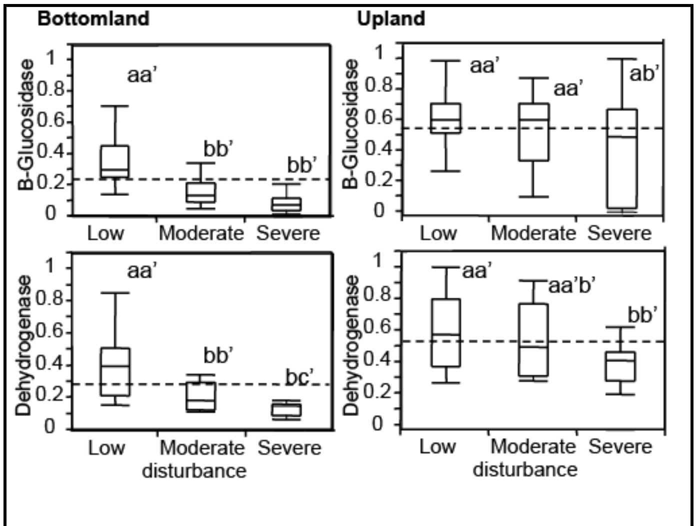

Figure 4.
Comparison of normalized β-glucosidase and dehydrogenase values for soils from Low, Moderate, and Severe disturbance bottomland and upland transects. Separate means comparisons were performed for December and February (prime) values; different letters indicate significant differences ($\alpha < 0.05$ except February bottomland dehydrogenase $\alpha < 0.10$). Dashed line indicates mean for all samples. Median and quantiles are indicated for data from both sampling dates combined. The line in the body of each box represents the median; top and bottom of the box represent the 75th and 25th quantiles; the lines above and below each box represent the 10th and 90th quantiles.

Figure 20. Comparison of normalized β-glucosidase and dehydrogenase values for soils from Low, Moderate, and Severe disturbance bottomland and upland transects.

Relative bioavailability of soil C was higher in disturbed areas due to depletion of older, more stable soil organic matter (lower right Figure 20, previous page). Similar to Kryszik’s study, differences are significant for these parameters between the “low” and “severe” disturbance treatments. Like that study, these findings may suggest a shift from biological regulation to abiotic control of system dynamics. The response of qCO2 to soil disturbance was consistent with the responses of DOC:TC and MBC:TC, all of which suggest that resource (organic C) quality increased with soil disturbance, i.e., there was a lower proportion of recalcitrant soil organic matter, even as total soil C storage decreased with increasing disturbance.

Beta-glucosidase activity is an indicator of the amount of bio-available soil C. Bottomlands adjacent to three levels of military training could be distinguished using ß-glucosidase concentrations. These findings indicate a higher ratio of available carbon to TC at intermediate levels of disturbance. Separation of moderate from low and severe impacts by ß-glucosidase was less effective in upland soils.

Methanotrophic bacterial communities differ in highly impacted bottomlands. Terminal restriction fragment length polymorphism (T-RFLP) analysis of pmoA genes was applied to samples taken from transects located in upland and bottomland sites within the two watersheds.

Principal components analysis (PCA) revealed that T-RFLPs from upland and for the most part bottomland samples clustered together in both watersheds. However, some Bonham Creek bottomland T-RFLPs clustered within the upland cluster, suggesting mixing of upland with bottomland soils.

Vegetation

Table 3. Post clear cut age class, indicator value and significance for species identified as indicators.

Species	Post Clear Cut Age Class (years)	Indicator Value	p-value
Bulbostylus barbata	0-3	36.2	0.063
Cyperus croceus	0-3	43.7	0.034
Andropogon virginicus	8-10	62.1	0.002
Dichanthelium species	8-10	41.1	0.012
Sphagnum species	8-10	50.3	0.008
Sporobolus junceus	8-10	28.6	0.044
Pityopsis species	15-20	44.5	0.020
Tridens flavus	15-20	40.2	0.048
Desmodium species	15-20	39.8	0.034
Andropogon ternarius	30-80	36.3	0.028
Schizacharium scoparium	30-80	49.0	0.011
Schizacharium/Andropogon ternarius Complex	30-80	47.1	0.019
Hieracium species	30-80	36.7	0.024
Rhynchosia tomentosa	30-80	32.9	0.088

Plant species indicating various stages of recovery from severe disturbance were identified that may be useful in tracking the progress of restoration efforts in highly-impacted areas (Table 3). Herbaceous species composition and cover varied more with stand age than understory woody species. Species richness did not differ among age classes for either woody or herbaceous species, while species distribution and abundance did. *Bulbostylis barbata*, *Eupatorium capillifolium*, and *Pityopsis graminifolia* were identified as indicators of younger sites (those recently disturbed). Interestingly, these are not the same species as those being associated with significantly disturbed sites. *Andropogon virginicus*, *Dichanthelium spp.*, and *Aristida* spp. have all been found to be more abundant soon after a disturbance, followed by a slow decrease in frequency and abundance over time. *Schizachyrium scoparium* and *Andropogon ternarius* were associated with 30-80 yr sites.

Consistent with the other SEMP studies, training and land management disturbances affect percent cover and composition of herbaceous communities, or in cases of more severe impacts, canopy cover. Patterns of understory species composition correlate with disturbance. Clear species indicators are generally observed only at heavily impacted sites. Woody plants did not differentiate well among the disturbance levels; however, there was a trend of decreased overstory canopy cover with increased disturbance. The lack of differentiation may indicate either indifference in response or adaptation to a prolonged history of highly disturbed conditions. Herbaceous vegetation composition on severely-disturbed sites segregated from low and medium disturbances but no segregation was found between the two lower levels of disturbance. Chronic, landscape-scale disturbances have resulted in a very resilient flora, minimizing the abundance of certain life forms. Interest-

Table 4. Physical characteristics fo study watersheds. Acronyms BON-2, BON-2, BON, LPK, and SAL represent the steams (or watersheds) Bonham-2, Bonham-2, Bonham, Little Pine Knot, and Sally Branch, respectively..

Physical Characteristics	BON-1	BON-2	BON	LPK	SAL
Topography					
Area, km^2	0.76	2.21	12.73	18.01	25.31
Average Elevation, m	121.8	133.5	125.5	146.3	136.8
Average Slope, degree	5.46	4.89	5.04	5.32	5.42
Vegetation					
Pine, %	28	30	40	41	48
Deciduous, %	27	6	8	2	12
Mixed, %	39	50	22	34	15
Wetland, %	6	8	9	17	10
Military Land, %	0	6	5	2	2
NDVI	0.36	0.30	0.32	0.34	0.36
Soil					
Sand, %	78	69	69	72	49
Loam, %	9	9	31	28	51
Road					
Road Length, km	3.6	11.4	51.6	56.6	97.6
Road Density, km/km^2	4.8	5.1	4.1	3.1	3.8
Stream					
Stream Length, km	2.6	3.9	29.1	43.3	65.2
Stream Density, km/km^2	3.4	1.7	2.3	2.4	2.6
Stream Order	2	2	4	4	4
Other					
No. of Roads Crossing Streams	1	2	13	11	21
Bare Land, %	1	11	11	4	7
Disturbance Index, %	11	21	19	11	15

ingly, many typical early disturbance species appear less frequent and patchy in distribution on the landscape. A short list of species would include *Rubus cuneiformis, Toxidendron quercifolia, Eupatorium capillifolium*, and early successional Euphorbaceae. Similar to other SEMP findings, coverage of bare ground and plant litter may best serve as indicators of disturbance.

Plant species present only in severely disturbed sites identify the highest degree of disturbance. Consistent with Dale's findings, the relative cover of *Rubus* sp. and *Rhus copallina* may be an important indicator of a shift from moderate to severe conditions. Both species are prolific seed producers, bird dispersed, fire enhanced, and capable of colonize disturbed sites. Unlike the other woody species, these species are capable of withstanding physical disturbance. Those herbaceous species most closely associated with severely disturbed sites were: *Digitaria ciliaris, Diodia teres, Aristida tuberculosa, Aristida purpurescens, Opuntia humifusa, Haplopappus dirasicatus*, and a likely planted species, *Paspalum notatum*. Also noteworthy, with increasing disturbance and independent of family, the relative frequency and dominance of rhizome-, corm-, or bulb- species is reduced. Expectedly, highly disturbed areas have much higher frequency and dominance of annual forbs and grasses.

Hydrology

Correlation and regression analyses were performed to determine relationships among the watershed physical characteristics and the storm-based hydrologic indices. A number of significant relationships were found through these comparisons. Consistent with other SEMP projects, correlation results show that the increase in road density increased the variability in the peak discharges and the slopes of the rising limb (Table 4). The increase in the military land increased the time of rise as well as the variability in the time base. The number of roads crossing streams is positively correlated with the response lag, whereas it was negatively correlated with the time base and the variability in the slopes of the falling limb. Increase in the bare land and the disturbance index increased the time of rise as well as the variability in the time base. Stepwise multiple correlations identified the relationships between the event indices and the management related watershed physical characteristics that are susceptible to the disturbances. Military land, road density, and the number of roads crossing streams predicted storm-based base flow index, bank full discharge, response lag, and time of rise well. These land-use criteria (Figure 21) are then strongly associated with biologically important stream parameters (rows in Table 4); thus, not unexpectedly, reflect stream quality.

Training impacts bulk density through compaction (Figure 21). An artifact effect is evident when offsite soils are comparted to non-training sites. Assuming similar past land-use, this suggests a residual training affect that persists when training sites are converted to "light-use." Figure 21 (bottom) indicates that infiltration rate is significantly diminished. This suggests that during heavy rainfall, the majority of the precipitation would be transferred as surface flow, which accelerates the risk of sheet erosion.

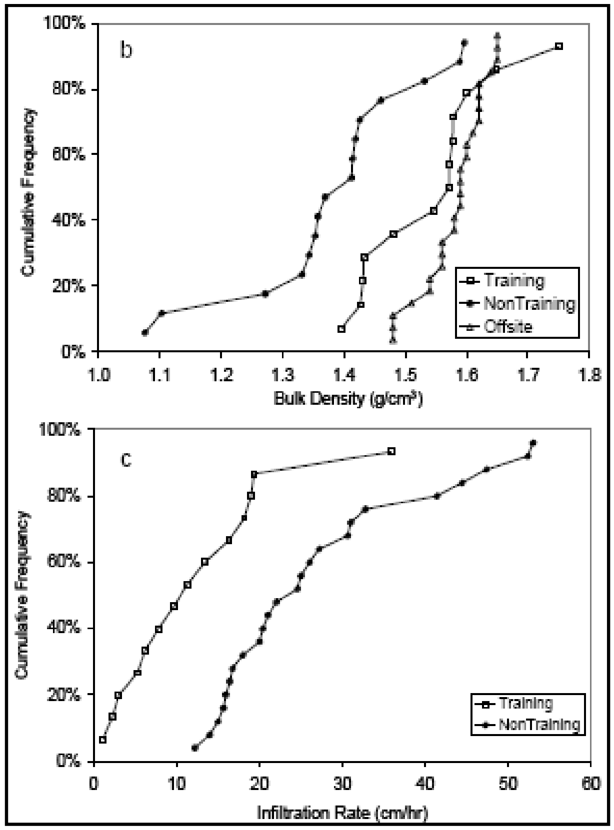

Figure 21. Land-use criteria.

Table 5. Pearson correlation coefficients between watershed characteristics and water quality parameters.

Table 4. Pearson correlation coefficients between watershed characteristics and water quality parameters. Characteristics are acronymed as follows: Pine forest (PIN), Deciduous forest (DCD), Mixed forest (MXD), Wetland (WET), Military land (MIL), Sandy Soil (SND), Loamy Soil (LOM), Road Length (RDL), Road Density (RDN), Stream Density (STD), Normalized Difference Vegetative Index (NDVI), No. of Roads Crossing Streams (NRC), % Bare Land (PBL), and Disturbance Index (DIN). *, **, and *** indicates significance at or below 0.05, 0.01, and 0.001 probability levels, respectively

	PIN	DCD	MXD	WET	MIL	NDVI	PBL	DIN	SND	LOM	RDL	RDN	NRC	STD
pH	0.36	-0.47	-0.79*	0.24	0.09	0.32	-0.45	-0.65	-0.50	0.57	0.94***	-0.75*	0.93***	-0.14
Temperature	0.78	-0.37	-0.55	0.62	0.00	0.11	-0.25	-0.36	-0.02	0.16	0.95***	-0.42	0.59	-0.11
Conductivity	0.54	-0.40	-0.38	0.44	-0.10	0.10	-0.51	-0.60	0.14	0.03	0.82*	-0.54	0.51	-0.01
TKN	0.00	-0.12	-0.39	0.11	-0.50	0.60	-0.72	-0.84*	-0.19	0.39	0.19	-0.72	0.36	0.39
TP	-0.09	-0.33	-0.83*	-0.11	0.10	0.46	-0.42	-0.63	-0.78*	0.81*	0.57	-0.78*	0.90**	-0.04
TOC	0.15	0.39	-0.24	0.18	-0.87**	0.80*	-0.81*	-0.76*	0.15	0.07	0.09	-0.35	0.06	0.82*
Cl	0.56	0.13	-0.49	0.37	-0.47	0.55	-0.68	-0.65	0.06	0.07	0.79*	-0.32	0.47	0.44
TSS	-0.14	0.42	-0.11	-0.29	-0.53	0.54	-0.87**	-0.72	0.15	-0.14	0.30	-0.15	0.19	0.65

Table 6. Stepwise multiple regression models for water quality parameters.

Table 5. Stepwise multiple regression models for water quality parameters. pH is unitless, temperature is measured in degrees centigrade, conductivity is measured in µS/cm, TP, TKN, TOC, Cl, and TSS are measured in mg/L. Pine forest (PIN), Military land (MIL), Sandy Soil (SND), Loamy Soil (LOM), Road Length (RDL), Road Density (RDN), No. of Roads Crossing Streams (NRC), Percent Bare Land (PBL), and Disturbance Index (DIN) are the independent variables retained in the regression analyses. *, **, and *** indicates significance at or below 0.05, 0.01, and 0.001 probability levels, respectively

Water Quality Parameters	Independent Variables Retained and Regression Equations	R^2
pH	Pine, Road Length 5.50 – 0.0382 PIN + 0.00924 RDL	0.98***
Cl	Military, Road Length 2.19 + 0.145 MIL + 0.00344 RDL	0.90**
TP	No. of Roads Crossing Streams 0.00451 + 0.000236 NRS	0.81**
Conductivity	Sandy Soil, No. of Roads Crossing Streams - 24.2 + 0.552 SND + 0.666 NRS	0.80*
Temperature	Loamy Soil, Road Density 26.1 – 0.051 LOM – 1.49 RDN	0.77*
TOC	Military Land 3.45 – 0.274 MIL	0.76**
TSS	Percent of Bare Land 11.2 – 0.648 PBL	0.76**
TKN	Disturbance Index 0.445 - 0.0109 DIN	0.70*

Analysis of hydrographs clearly reflects hydrologic imbalances resulting from soil and vegetation disturbance in uplands. In support of the finding that uplands in non-impacted areas do not contribute to the stream hydrograph, the contributing areas calculated by the stream hydrograph volumes and depth of rainfall events was less than the riparian/wetland area, suggesting that no area outside of the wetland/riparian area contribute to the stream hydrographs. In training areas, the K_{sat} values were sufficiently low that overland flow could occur. Time of concentration for a 10cm/hr storm event was about 10 minutes. Based on appearance, overtime overland flow events within heavily impacted areas have gouged out deep gullies and transported sediment from the hilltops. The flow processes in these areas are observed to be different than those in less-impacted watersheds. Overland flow was conceived to usher water toward roads that channel the water directly to streams, thus by-passing or short-circuiting the natural watershed flow paths.

Canopy interception averaged about 17% of precipitation and varied seasonally as well as between habitat types (Table 5). Closed canopies had higher percentages of intercepted precipitation when compared to open forest settings; deciduous canopies had lower interception during dormant periods (winter). Interception saturation was correlated with Leaf Area Index (LAI), whereby greater amounts of throughfall and stem flow occurred with larger storms. Intercepted precipitation was returned through evapotranspiration and foliar absorbance. Depending upon storm intensity, 2-15% of throughfall and stem flow volume ends up as stream flow within a 24 hour period. The remainder is stored within the soil. Time to peak throughfall discharge from the canopy is approximately 3 hours.

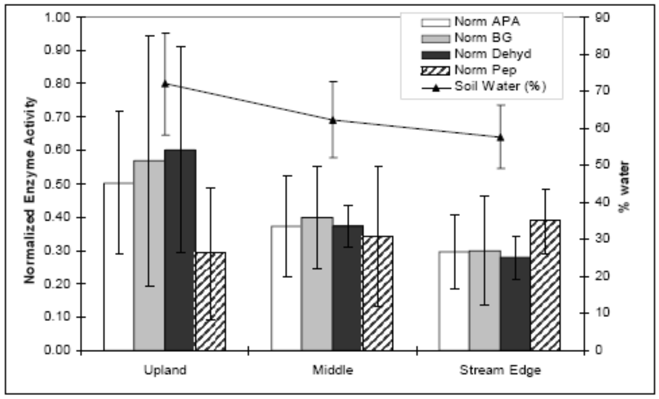

Figure 2.
Mean normalized soil enzyme activities and soil moisture levels from three transects perpendicular to Bonham-2 stream flow. Error bars indicate one standard deviation. Enzyme activities were normalized to the highest value for each enzyme from all sites. Two soil samples (0-10 cm depth) were composited from within 1 m^2 at approximately 5, 10 and 15 m from streambank. APA, acid phosphatase activity; BGA, β-glucosidase; Pep, peptidase; Dehyd, dehydrogenase.

Figure 22. Mean normalized soil enzyme activities and soil moisture levels from three transects perpendicular to Bonham-2 stream flow.

Table 7. Measured precipitation, throughfall, and derived streamflow for 4/04/01 through 6/11/02.

Table 2. Measured precipitation, throughfall, and derived stemflow for 4/04/01 through 6/11/02. Plots are acronymed as follows: Wetland (WET), Pine (PIN), Pine Plantation (PIP), Hardwood (HRD), and Mixed (MXD).

	WET	PIN	PIP	HRD	MXD
Measured precipitation (mm)	752.8	752.8	724.8	724.8	684.9
Measured throughfall (mm)	614.5	580.8	583.3	594.5	553.8
Coefficient of variation of measured throughfall	0.17	0.15	0.14	0.17	0.14
Stemflow (mm)	4.9	4.1	14.2	3.9	3.7
Actual interception (mm)	133.4	167.9	127.3	126.4	127.4
Throughfall % of precipitation	81.6	77.2	80.5	82.0	80.9
Stemflow % of precipitation	0.65	0.54	1.96	0.54	0.54
Interception % of precipitation	17.7	22.3	17.6	17.4	18.6

Table 2. Summary of soil chemical analyses by watershed. The number of low, moderate, and severely disturbed bottomland and upland sites included in the analysis are indicated. Values are mean ± std. dev. Different letters indicate significant differences at $\alpha < 0.05$.

Watershed	Number of sites sampled			Mehlich Extractable				Water Ext.	Total		
	Low	Mod.	Severe	Ca mg kg^{-1}	Fe mg kg^{-1}	Al mg kg^{-1}	K mg kg^{-1}	C mg kg^{-1}	C g kg^{-1}	N g kg^{-1}	P mg kg^{-1}
Bottomlands											
Bonham	11	2	1	46 ± 43^{a}	246 ± 247^{a}	626 ± 659^{a}	27 ± 20^{a}	163 ± 101^{a}	34.2 ± 33.2^{a}	1.67 ± 1.53^{a}	181 ± 113^{a}
Halloca	10	3	0	251 ± 160^{a}	344 ± 392^{a}	386 ± 290^{a}	38 ± 18^{a}	88 ± 37^{b}	17.7 ± 9.8^{a}	1.10 ± 0.69^{a}	181 ± 105^{a}
Randall	14	5	0	136 ± 159^{a}	152 ± 93^{a}	459 ± 399^{a}	29 ± 14^{a}	77 ± 34^{bc}	22.2 ± 17.8^{a}	1.27 ± 0.99^{a}	118 ± 57^{a}
Sally Branch	7	4	2	84 ± 75^{a}	242 ± 181^{a}	556 ± 510^{a}	38 ± 22^{a}	39 ± 22^{bc}	29.2 ± 22.2^{a}	1.56 ± 1.25^{a}	191 ± 142^{a}
Shell	10	0	0	683 ± 512^{b}	193 ± 281^{a}	192 ± 85^{a}	73 ± 35^{b}	23 ± 4^{c}	13.3 ± 4.5^{a}	0.75 ± 0.24^{a}	137 ± 55^{a}
Wolf	12	1	0	46 ± 27^{a}	163 ± 119^{a}	654 ± 338^{a}	27 ± 10^{a}	56 ± 34^{bc}	29.0 ± 10.5^{a}	1.65 ± 0.67^{a}	190 ± 100^{a}
Uplands											
Bonham	9	18	8	30 ± 23^{a}	23 ± 10^{a}	169 ± 70^{a}	8 ± 7^{a}	131 ± 55^{a}	7.7 ± 3.5^{a}	0.30 ± 0.12^{a}	68 ± 27^{a}
Halloca	1	20	9	157 ± 213^{b}	42 ± 19^{b}	269 ± 118^{b}	29 ± 24^{b}	65 ± 26^{b}	8.8 ± 4.6^{ab}	0.36 ± 0.20^{a}	68 ± 38^{a}
Randall	14	19	3	73 ± 69^{ab}	37 ± 24^{b}	258 ± 101^{b}	16 ± 7^{ab}	62 ± 23^{bc}	9.7 ± 3.9^{ab}	0.34 ± 0.14^{a}	62 ± 30^{a}
Sally Branch	5	27	2	111 ± 169^{ab}	29 ± 12^{ac}	174 ± 79^{a}	22 ± 22^{ab}	41 ± 34^{cd}	10.9 ± 4.9^{bc}	0.37 ± 0.13^{a}	69 ± 25^{a}
Shell	16	8	2	532 ± 344^{c}	40 ± 19^{bc}	275 ± 67^{b}	84 ± 44^{c}	39 ± 23^{bd}	13.4 ± 4.5^{c}	0.62 ± 0.21^{b}	108 ± 36^{b}
Wolf	3	19	2	65 ± 51^{ab}	31 ± 12^{ab}	295 ± 101^{b}	17 ± 7^{ab}	34 ± 17^{d}	10.7 ± 4.0^{ac}	0.37 ± 0.12^{a}	74 ± 31^{a}

Figure 23. Summary of soil chemicla analyses by watershed.

Soil physical parameters (bulk density, porosity, texture, grain-size distribution, and saturated hydraulic conductivity) are potentially useful at small spatial scale. Smaller scaling factors imply smaller mean pore sizes of the training soils compared to the non-training soils. The higher soil bulk density values and lower infiltration rates of the training versus non-training areas are indications of the loss of organic matter combined with compaction from repeated tank track. The mean steady-state infiltration rate of the training sites (12.0 cm/hr) is less than half that of the non-training sites (26.8 cm/hr), but it is still greater than the maximum 100-yr, 24-hr rainfall intensity of 10 cm/yr. This indicates that storm intensities are usually <Ksat at most places, except severely disturbed areas and that vegetation cover plays an important role in determining the potential runoff and may be more important than Ksat of surface soil.

Stream water quality

Water quality measurements revealed low levels of most nutrients, in fact, many elements and compounds are at or below the detection limit for commonly used detection equipment; thus, a defacto stream quality indicator would be measurable concentrations of nitrate, ammonium, phosphorus, or metals. Stream TOC and Total Kjeldahl Nitrogen (TKN) concentration decreased with increasing soil and vegetation disturbance (proportion of bare ground) in the watershed, reflecting depletion of soil organic matter and detritus in uplands and reduced leaching in soils due to short-circuited flow paths (gulleys) from uplands to streams.

Enzyme activities relative to patterns of biogeochemistry and soil water content in riparian wetlands varied with distance from stream edge and help explain temporal patterns of groundwater TKN related to leaf fall and canopy loss in riparian forests. The transition from the upland to flanking slope transitions then to the wetland forest have change in total N as well as available N (NH4+), the change in the relationship between total and available reflect changes in soil enzyme activity. The differences are also likely to reflect watershed storage source-sink patterns, the importance of slope and streamside buffers, as well as system capacitance. Further, these patterns are likely to reflect changes in soil textural profile, soil moisture, organic content, as well as resultant anion and cation exchange capacity.

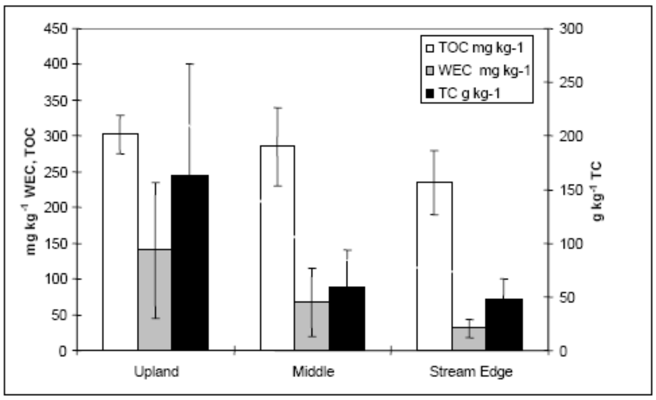

Figure 3.
Total organic carbon (TOC), water extractable carbon (WEC), and total carbon (TC) from transects perpendicular to Bonham-2 stream flow. Values are means of three transects; error bars indicate one standard deviation. Two soil samples (0-10 cm depth) were composited from within 1 m^2 at approximately 5, 10 and 15 m from streambank. Units are mg Kg^{-1} (TOC and WEC) and g Kg^{-1} (TC).

Figure 24.

Riparian zones and wetland vegetation is significantly impacted by sedimentation that leads to decreased canopy cover in wetlands and hardwood communities. Nutrient and sediment loads in “low” and “medium” impact sites are not too large. Sediment may be the most important water quality attribute for “severe” impact sites. Disturbed riparian zones, adjacent to impacted areas, have limited nutrient storage and retention capacity which results in increased nutrient load to streams. Therefore, riparian zone condition plays an important role in determining water quality.

Modeling and Synthesis

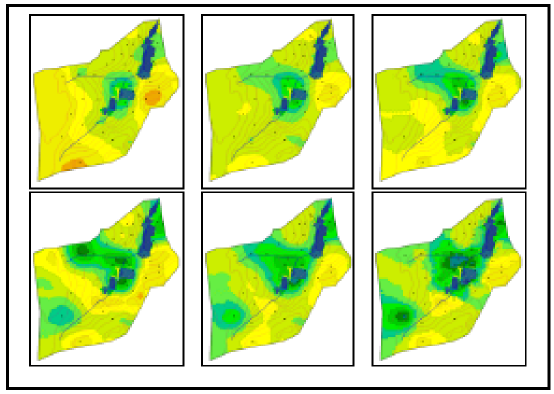

Figure 25. Depth-specific water content estiamtion maps of Bonham-1 watershed for March 2002. Blue areas contain more water than yellow and brown areas.

Comparable to Collins SEMP findings using NMDS, various multivariate analyses yielded combinations of factors that are useful in identifying impacts. Multivariate statistical analyses were applied to 20 biogeochemical parameters in order to discriminate samples based on landscape position, vegetation type, watershed of origin and disturbance class. Principal components analysis identified that the total organic matter present in the soil samples (measured as total carbon, total nitrogen, and total phosphorous) was the dominant contributor of variability between the soil samples. Canonical Discriminant Analysis showed that canonical variables could be successfully used to discriminate samples based on landscape position, vegetation type, watershed of origin, and disturbance class. Logistic regression was used to predict the probability of a specific site being disturbed or non-disturbed based on the observed categorical variables and measured biogeochemical variables that were found to effect disturbance

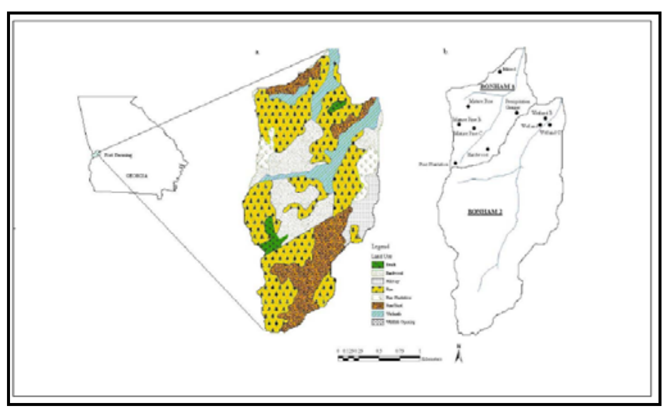

Figure 26. Bonham-1 and Bonham-2 study watersheds in Fort Benning, GA with (a) land use distribution, and (b) plot locations for interception determination indicated.

Near Infrared Reflectance Spectroscopy (NIRS) for soil analysis is rapid, low-cost technique for determination of several individual soil biogeochemical properties and direct evaluation of derived soil quality metrics or indices. Reflectance measurements and 20 soil biogeochemical variables measured on over 550 soil samples were used to develop a robust PLS model for independently predicting 18 soil parameters including various forms of carbon and nutrients. When compared with results from traditional analyses, Total C, Total P, Total N, Oxalate-extracted available Iron, Oxalate-extracted available Phosphorus, and Microbial Carbon were predicted accurately (Table 8). Though measures of available nutrients are often much better correlated with site quality and productivity, those measures are also limited by the fact that "available" nutrients may in fact not be limiting in plants or may not be seasonally available for root uptake during periods of high demand. Overall, the results indicate that near-infrared spectroscopy (NIRS) coupled with partial least squares analysis can be a useful and inexpensive alternative to expensive and time consuming lab analyses; therefore, independently or as a model component, may be useful in assessing or monitoring changes in soil quality and site productivity and the influence of military land-use.

Table 8.PLS prediction results for 18 soil biogeochemical variables of phase 2 soil data.**

Soil Properties	Number	Mean Error	SEP• δ	EF••	RPDδ	RERδ
pH	124	0.036	0.457	0.000	0.990	6.973
Ash	124	0.023	0.056	0.101	1.055	5.787
Total Carbon	124	0.078	0.213	**0.868**	**2.760**	**10.98**
Total Phosphorus	123	0.006	0.176	**0.767**	**2.072**	**9.334**
Total Nitrogen	119	0.013	0.212	**0.888**	**2.989**	**11.70**
Oxalate Al	71	0.040	0.184	0.068	1.035	4.791
Oxalate Iron	71	0.062	0.245	**0.759**	**2.037**	**7.632**
Oxalate Phosphorus	71	0.019	0.273	**0.611**	**1.603**	**6.017**
Mehlich Al	71	-0.435	0.626	-0.158	0.928	4.107
Mehlich Iron	71	-0.228	0.461	0.416	1.309	5.319
Mehlich Phosphorus	124	-0.024	0.433	-0.049	0.976	4.826
Mehlich Mg	71	-0.604	0.923	-0.594	0.792	3.377
Mehlich Potassium	71	-0.460	0.694	-0.419	0.839	3.401
Mehlich Calcium	71	-0.036	0.444	-0.597	0.791	4.241
Microbial Carbon	124	-0.020	0.232	**0.705**	**1.842**	**8.596**
Water ext. Carbon	124	-0.180	0.507	0.041	1.021	4.775
Water ext. Phosphorus	124	-0.193	0.708	-0.044	0.978	3.227
KCl ext. NH_4	124	0.139	0.322	-0.305	0.875	4.602

• •Forecasting Efficiency
• •Standard Error of Performance
δ Defined in the text.
• •MBN and MBP didn't have measured data for the independent dataset.

Journal articles

Published

Bryant, M.L., S. Bhat, and J.M. Jacobs. 2005. Spatiotemporal throughfall characterization of heterogeneous forest communities in the southeastern U.S. Journal of Hydrology. (2005):1-14.

Bhat, S., J.M. Jacobs, K. Hatfield, and J. Prenger. 2006. Ecological indicators in forested watersheds: relationships between watershed characteristics and stream water quality in Fort Benning, GA. Ecological Indicators. 6(2) 458-466.

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Bhat, S., K. Hatfield, J. M. Jacobs, R. Lowrance and R. Williams. 2007. Surface runoff contribution of nitrogen during storm events in a forested watershed. Biogeochemistry. Available online: http://www.springerlink.com/content/100244/?Content+Status=Accepted

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Accepted/in press

Bhat, S., J. M. Jacobs, K. Hatfield, and W. D. Graham. 2007. Ecologically Relevant Storm-Based and Annual-Based Indices of Hydrologic Variability in Military Lands. Hydrological Processes. Under Review.

Bhat, S., J. M. Jacobs, K. Hatfield, and W. D. Graham. 2007. Development of Ecologically Relevant Storm-Based Indices of Hydrologic Variability. Ecological Indicators. Under Review.

Cohen, M.J., S. Dabral, W.D. Graham, J.P. Prenger, and W.F. DeBusk. Evaluating ecological conditions using soil biogeochemical parameters and near infrared reflectance spectra. Environmental Modeling and Assessment. (Accepted)

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Submitted

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Dabral, S., W.D. Graham, and J.P. Prenger. Quantitative analysis of soil nutrient concentrations with near infrared spectroscopy and partial least squares regression. Soil Science Society of America Journal. (Submitted March 2004)

Perkins, D., N. Haws, S. Rao, J. Jawitz. Hydraulic conductivity of upland soils in forested watersheds at Fort Benning, GA: assessment of mechanized military training. Vadose Zone Journal. (Submitted April 2004)

Prenger, J.P., W.F. DeBusk, and K.R. Reddy. Influence of military land management on extracellular soil enzymes. Soil Biology and Biochemistry. (Submitted December 2004)

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Tanner, G.W. and D.L. Miller. Vegetative indicators of disturbance in a chronically-disturbed ecosystem, Fort Benning Army Reservation, Georgia. Ecological Restoration. (Submitted April 2004)

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Bryant, M.L. 2002 Spatiotemporal throughfall characterization of heterogeneous forest communities in the southeastern U.S. M.S. Thesis. University of Florida

Chen, W. 2001. Optimization of terminal restriction fragment length polymorphism and evaluation of microbial community structure as indicator of ecosystem integrity. M.S. Thesis. University of Florida.

Perkins, D. 2003. Soil hydrologic characterization and soil-water storage dynamics in a forested watershed. M.S. Thesis. Purdue University.

Skulnick, B.L. 2002. Soil carbon biogeochemistry: indicators of ecological disturbance. M.S. Thesis. University of Florida.

Tkaczyk, M. 2002. Rainfall runoff and subsurface flow analysis to investigate the flow paths in forested watersheds utilizing TOPMODEL. M.S. Thesis. University of Illinois at Chicago.

SEMP Project CS-1114B-00: Development of ecological indicator guilds for land management (PI: A. Krzysik, Prescott College)

Overall, this study involved using a two phase approach with nested plots in locations that represented 5 levels of training intensity within the upland forest. Based on literature, eleven potential ecological guilds initially used; eight of these guilds were very successful in discriminating among disturbance classes. Each guild consisted of several measured parameters that have direct functional relationships or are correlated with compounded processes. Guilds were associated with other guilds and ecosystem features using multivariate techniques, such as path analysis, MANOVA, and discriminant function analysis, to develop correlative relationships between conditional features and criteria used to select training intensity. The most effective discriminating guilds included: (1) general habitat characteristics, (2) general ground cover characteristics, (3) general ground cover floristics, (4) microbial community dynamics, (5) soil chemistry processes, (6) nutrient leakage, (7) soil mineralization potential, and (8) ground surface/forest floor ant communities.

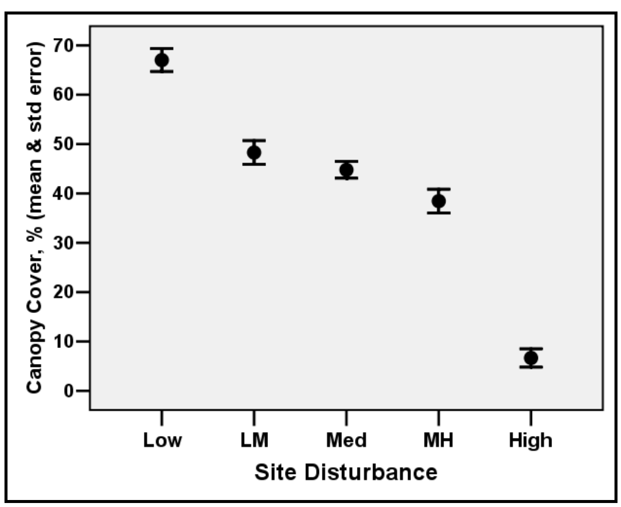

Figure 27. Site disturbance correlation with canopy

cover.

The remaining three ecological guilds included; developmental instability, plant physiology, and plant community structure. Developmental instability was not found to be useful because of volatile responses to changes by other regulating parameters that are independent of disturbance (e.g., genetic isolation, facilitation). Plant physiology and plant community structure are complex bi-product relationships of smaller scale and larger scale processes, respectively. Both are expected to shift and respond to disturbance, however, these changes are likely to be at time scales beyond the scope of this study. For example, habitat differentiation based on physiological adaptation will require genetic shifts at the population level. Similarly, shifts and reorganization of plant community structure will require dispersion and establishment of better suited species.

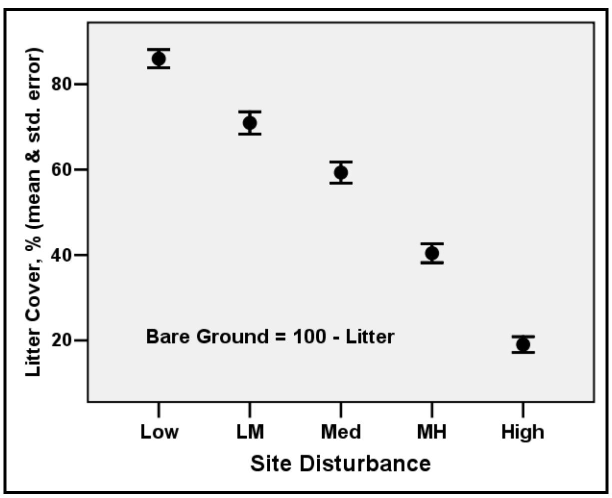

Figure 28. Site disturbance correlation with litter cover.

All eight successful EI guilds in Phase I, differing widely in tracking ecosystem condition and responses, demonstrated that the Low and Medium disturbance classes were similar to each other, but differed a great deal from the "High" disturbance sites. This likely indicates that "Medium" disturbed sites may be well on their recovery trajectory from past military training activities. Nevertheless, Low and Medium sites were also successfully differentiated by all eight EI guilds. Discriminant analysis results from these guilds were consistent. Therefore, Discriminant analysis consistently provided a quantitative assessment of the relative ecological differences among the three disturbance classes (i.e., the relative locations of the three disturbance classes in discriminant space).

Collectively, it is important to recall that the Fort Benning landscape has been subjected to a wide variety of landscape disturbances: historical agricultural activities (including associated infrastructure), historical major and recent managed timber harvest events, recent mechanized U.S. Army mechanized infantry training, and frequency of burning.

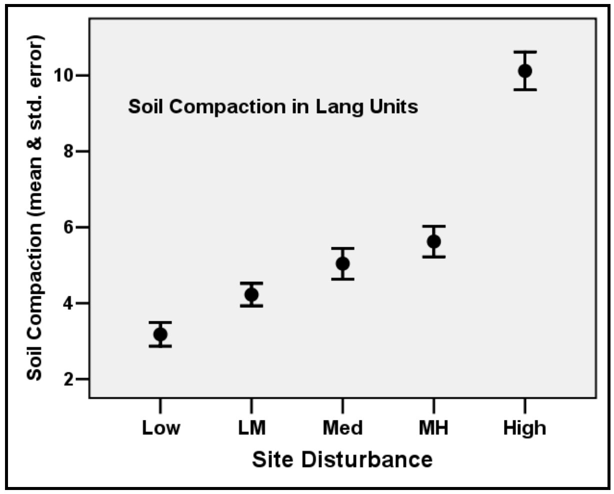

Figure 29. Site disturbance correlation with soil compaction.

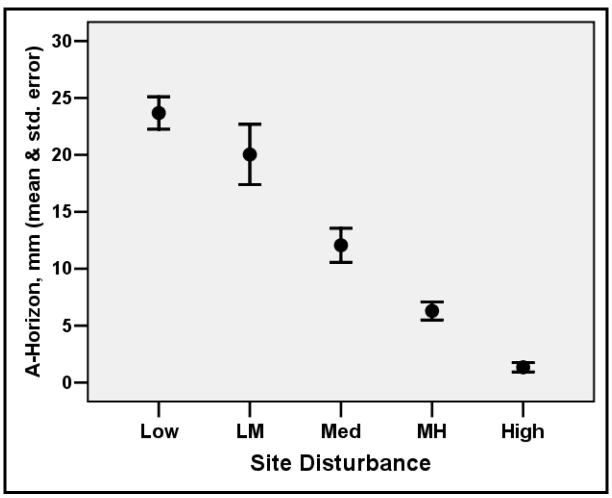

Figure 30. Site disturbance correlation with A-horizon.

Historical environmental disturbances although quantitatively unaccountable, undoubtedly significantly alter, often appreciably, and facilitate current ecosystem structure, dynamics, and processes. Present day plant community species composition and species richness in northeastern France are the direct result of agricultural intensity during the period AD 50-250 (Dupouey et al. 2002). Therefore, soil degradation from past land-use may be irreversible on historical time scales. Related, SEMP studies by Garten (2005) and Collins (2005) indicate that disturbance recovery rates slow rapidly with increased surface sand content.

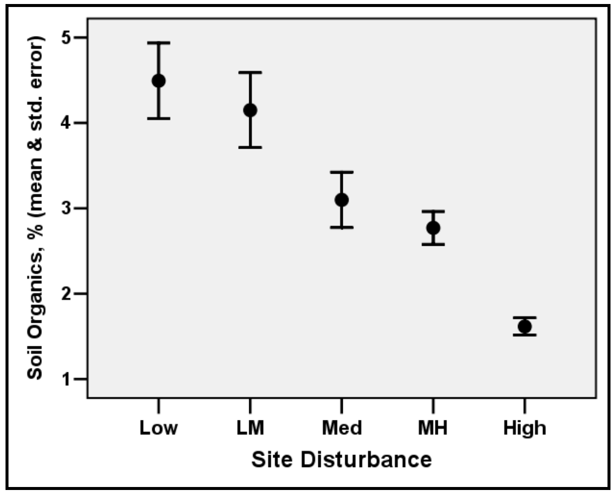

Figure 31. Site disturbance correlation with soil organics.

Field measures of ecosystem condition and properties, and their reference to disturbance, represent a cumulative reflection of all historical and current disturbances (anthropogenic, natural). Legacy disturbances, intensities, duration, and frequency regimes are not subject to detailed unraveling for most landscapes. Nevertheless, the careful selection of relatively pristine reference sites statistically contrasted to a broad landscape disturbance gradient has identified important Ecological Indicators (EI) of habitat disturbance, with the opportunity to analytically associate indicator metrics with ecosystem structure, function, and processes; and therefore, providing important monitoring capabilities for land managers: (1) general habitat characteristics, (2) general ground cover characteristics, (3) microbial community dynamics, (4) soil chemistry processes, (5) nutrient leakage, (6) soil mineralization potential, and (7) ground surface/forest floor ant communities.

A-horizon depth and soil compaction were the only EI metrics among all independent habitat parameters that successfully and significantly ($P<0.001$) distinguished among the three disturbance classes. These two EIs and soil mineralization potential (consists of two metrics) were the only metrics that on their own could distinguish the three disturbance classes. Soil is considered the major template for maintaining ecological processes and landscape sustainability (Herrick 2000, Johnston and Crossley 2002, Coleman et al. 2004). The A-horizon forms at the soil surface were humus accumulates, and is the layer of highest biological activity (Perry 1994, Ellis and Mellor 1995).

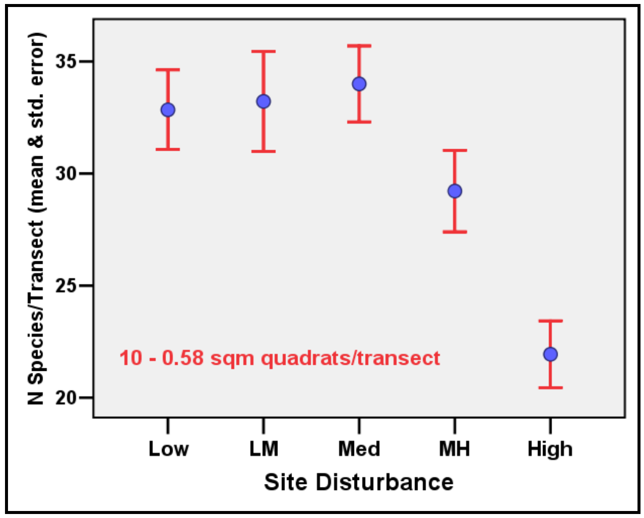

Figure 32. Site disturbance correlation with N species transect.

Relative to the plant community guild, composition and cover of the understory reflected disturbance intensity. With 126 taxa considered during phase II, 24 species significantly contributed to the disturbance gradient discriminant solution for the ground cover guild. Ground cover includes shrubs and tree seedlings <2 m in height. These taxa groups included eight large shrub and tree species seedlings as well as the following low shrubs, forbs, and grasses. Low disturbance species include: deerberry (*Vaccinium stamineum*), bull nettle (*Cnidoscolus stimulosus*), lance-leaved coreopsis (*Coreopsis lanceolata*), low-medium disturbance sites had highest abundances of bracken fern (*Pteridium aquilinuum*), fragrant sumac (*Rhus aromatica*), medium disturbance sites include higher abundances of sparkleberry (*Vaccinium arboretum*), lousewort (*Pedicularis canadensis*), poison ivy (*Rhus radicans*), bedstraws (*Galium spp.*), whorled coreopsis (*Coreopsis major*), rattlesnake weed (*Hieracium venosum*), medium-high disturbance sites support broomsedge (*Andropogron virginicus*), butterfly pea (*Clitoria mariana*), dog-fennel (*Eupatorium capillifolium*), and high disturbance sites support low densities of sand blackberry (*Rubus cuneifolius*), rough fleabane (*Erigeron strigosus*), horseweed (*Conyza canadensis*), and ragweed (*Ambrosia artemisifolia*). All of these species are abundant and widespread in the Southeast. Therefore, their ability to successfully identify the disturbance gradient and separate the disturbance classes makes this an important ecological indicator guild.

The microbial community dynamics guild, although successful in separating the disturbance classes, was a significant challenge for statistical inference and interpretation. Because both bacteria and fungi respond to and closely track moisture, temperature, and seasonal availability of litter, detritus, and nutrients; assessing habitat disturbance within this environmentally noisy background will remain a sampling and analysis challenge. Analysis did indicate that seven substrate guilds could be distinguished based on different patterns of utilization (rhizosphere activity, functional richness) by bacteria and fungi as well as differences between uplands and lowlands.

Guilds of soil chemistry processes, nutrient leakage, and soil mineralization reflected inter-related processes that could be collectively combined with microbial community dynamics. Higher soil organic matter and lower pH was associated with less disturbed sites. Surprisingly, microbial biomass carbon did not differ among disturbance classes, though microbial activity rates and organic substrate clearly differed between disturbance classes. Other nutrient and soil chemistry patterns include: (1) Lowland sites exhibited more consistent and greater ion concentrations than upland sites, (2) moderately disturbed lowland sites retained ions (sodium, potassium, magnesium, and sulfate) better than either less or higher disturbed sites, (3) highly disturbed upland sites leached more nitrate than less disturbed sites, (4) due to vegetation uptake, nitrate concentrations were lowest at the least disturbed sites, and (5) soil mineralization characteristics (rates, pathways) were very strongly associated with habitat disturbance.

The Soil Chemistry guild needs to be closely analyzed and integrated with the microbial guild. This analysis demonstrated that nitrate has low concentrations at Low disturbance sites, presumably because of more rapid nutrient uptake by more abundant vegetation or stronger and more stable links to mycorrhizal associations. Higher soil organic matter and lower pH was associated with less disturbed sites. The lower pH is due to the presence of humic acids resulting from decomposition processes. It was surprising that microbial biomass carbon did not differ among disturbance classes. This may be a terrestrial example of the "paradox of the plankton" where *biomass* trophic pyramids are reversed because of the higher turn-over rates of phytoplankton compared to zooplankton. In this case, the disturbance classes differ in microbial activity rates (as found in the microbial guild), while maintaining approximately the same biomass, an interesting observation.

The Nutrient Leakage guild was subjected to unequal sample sizes among years, sites, seasons, and habitats, because of drought conditions and physical damage to lysimeters by wildlife, especially feral hogs. Lowland sites exhibited more consistent and greater ion concentrations than upland sites. Moderately disturbance lowland sites retained ions (sodium, potassium, magnesium, and sulfate) better than either less or higher disturbed sites. Highly disturbed upland sites leached more nitrate than less disturbed sites.

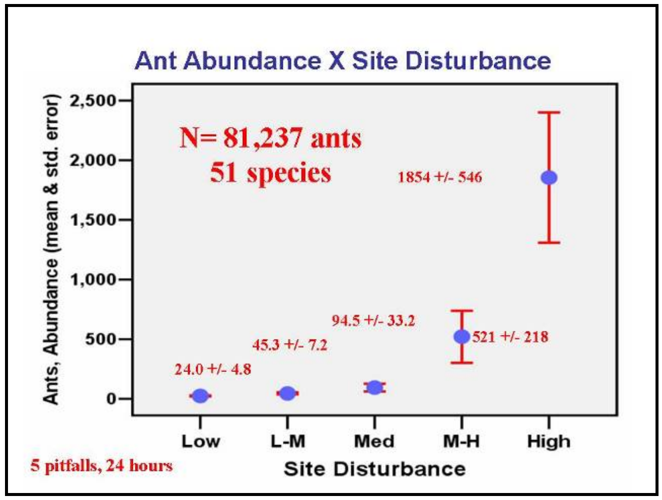

Figure 33. Site disturbance correlation with ants abundance.

The Soil Mineralization Potential guild was successful at assessing habitat disturbance, and shows promise as an indicator for assessing and monitoring forest ecological condition, see Kovacic et al. (2005) for more interesting details.

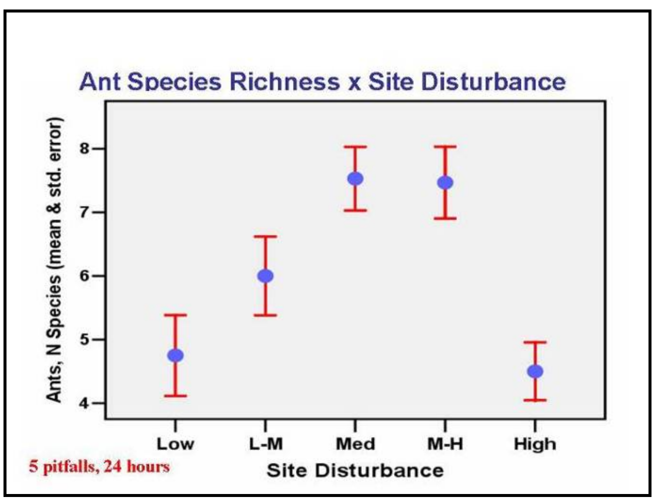

Figure 34. Site disturbance correlation with ants N species.

The Ground/Litter Ant Community guild with 28 species (103,203 individuals) was very successful at discriminating among the three disturbance classes. *Dorymyrmex smithi* comprised 87% of all individuals. This species requires warm nests and prefers habitats with open canopy and bare soils, and therefore, dominated the highest disturbed sites and the discriminant analysis. Nevertheless, the removal of the species for subsequent analyses had no effect on analysis results, indicating the robustness of the ant community as an effective and reliable EI guild. Five species of ants (554 individuals) were particularly successful at discriminating the disturbance gradient: *Aphaenogaster floridana*, *Camponotus castaneus*, *Letptothorax texana*, *Paratrechina parvula*, and *Solenopsis molesta* (native fire ant). The abundant imported fire ant (*Solenopsis invicta*) was in the 28 species analysis, but did not contribute significantly to disturbance class discrimination. A great deal of detailed information is available in Graham et al. (2004, 2005).

The ground/litter ant community guild with 28 species was very successful at discriminating among the three disturbance classes. Habitat specificity was primary due to species differences in nest requirements (openness, temperature, soil texture) and food habit differentiation. The dominant ant species (*Dorymyrmex smithi*) and five others (*Aphaenogaster floridana*, *Camponotus castaneus*, *Letptothorax texana*, *Paratrechina parvula*, and *Solenopsis molesta*) were particularly successful in discriminating differences along the disturbance gradient. Because ants, and other insect communities, tend to be aggregate representatives of habitat conditions at a scale comparable to disturbance patterns, they are an attractive "indicator." Further, ants can be sampled with limited daily access to monitored locations. Unfortunately, ant species classification can be difficult, and relatedness to regulatory standards as well as management criteria and concepts of "desired future conditions" is limited. A potential alternative is to use Lepidopterans or Orthopterans which better reflect vegetation and are more sensitive to habitat fragmentation features.

Unlike the other individual sampled metrics, two were proven to be effective at distinguishing between disturbance groups; A-horizon (surface horizon) thickness and measures of compaction. Unlike more visually apparent features, A-horizon thickness and compaction would have been difficult to us as *a priori* criteria for site selection or group assignment.

It was indeed encouraging to learn that EIs that reflected and mirrored complex ecosystem properties and their dynamics, and community structure and composition were relatively simple; and could economically be monitored by land managers without specialized knowledge, laboratory equipment, or taxonomic expertise. Research is actively continuing with the emphasis on multivariate modeling to further weave the tapestry for understanding these complex relationships and interdependencies.

The eight successful EI guilds encompass a very broad range of ecological attributes and ecosystem processes, including: physical and chemical properties of soils, simple economically obtained properties of vegetation, understory & canopy floristics, biodiversity metrics, microbial dynamics assessed by how bacteria and fungi partition substrate utilization, nutrient dynamics and leakage, and the structure (species composition and relative abundance) of an ecologically important animal community – ants. A critical feature of these eight EI guilds was their robustness to persistent and major background disturbance perturbations at Fort Benning: weather (e.g., severe drought), prescribed burns, and soil disruption by feral hogs. These covariates were purposely not included in the extraction of EI guilds to assess if their confounding effects were overridden by the underlying disturbance gradient.

The use of indices to classify or characterize landscape parcels raises an interesting caveat. This is exactly analogous to the calculation of a diversity index, a frequently used index for environmental monitoring and environmental impact assessment. The diversity index consists of two metrics: species richness (i.e., number of species) and evenness (the relative abundances among individual species). Even though there is a high positive correlation between the index and species richness with the accumulation of many samples, one can never be sure which of the two components of the index is more important when comparing any two specific samples. Two samples with the identical species diversity index, may nevertheless, differ dramatically in community structure. One community may possess a very large number of species with highly skewed species-abundance patterns. In other words, there are a few dominants, but most species are very rare. The other community may have relatively few species, but each species possesses similar abundances. These are compositionally, and undoubtedly functionally as well, dramatically different communities, but are described as identical by a diversity index. Similarly, and more meaningful to a land manager, high basal area can be achieved by either relatively few giant trees or a high density of very small trees. The basal area metric alone cannot distinguish between these two extreme possibilities.

Using forward selection involving all measured parameters, a site condition index (SCI) was developed using eight parameters; A-horizon thickness, soil compaction, % soil organic matter, % litter cover, % canopy cover, basal area, tree density, and NDVI (normalized discriminant vegetation index). The latter, NDVI, was later dropped because it did not significantly contribute to the discriminant solution. Again, these are similar parameters that other SEMP studies identified and are consistent with those used in Forest Inventory Analysis and Forest Health Measurements (USFS, 1999).

Ecological Indicator Design Criteria

- Ease of use for land managers
- Cost effective
- Ecological relevance & value
- Reflect ecosystem dynamics and physiological stress
- Quantifiable with statistical estimates of accuracy & precision
- Robust & multi-scale
- EcoRegion application
- Global methodology extension
- Symmetry: track degradation & recovery/restoration
- Reasonable response times
- Reliable, consistent, unambiguous
- Incorporation of natural variance
- Known sensitivity to temporal sampling window
- Association with suites of stressors

Figure 35. Ecological indicator design criteria.

The site condition index scores successfully discriminated between disturbance intensity groupings. Those associated with biological condition (plant community guild, ant community guild) reflected past research hypotheses (intermediate disturbance condition). Collectively, these integrated scores better reflect disturbance patterns and are more meaningful than other single interpretation values (basal area, density, species diversity, etc.).

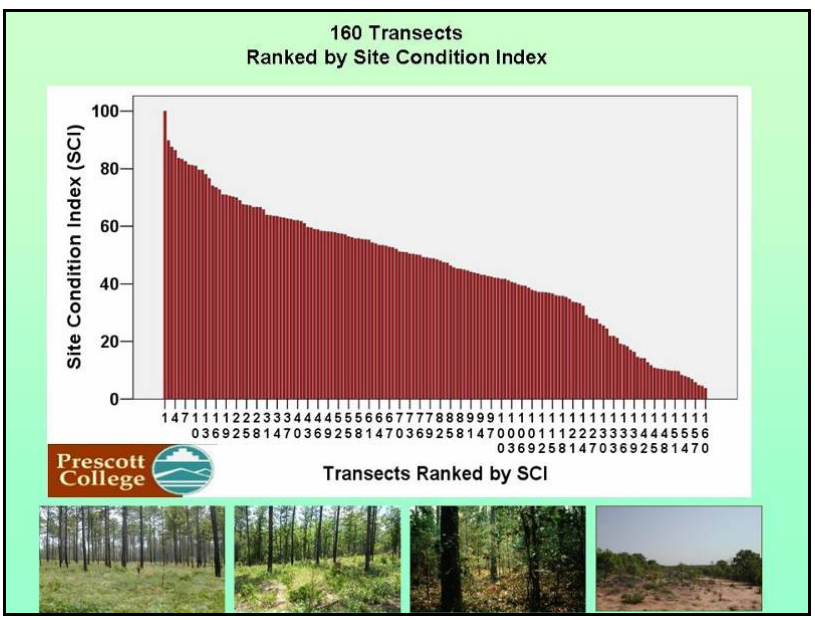

Figure 36. 160 transects ranked by site condition index.

Using a rank-order approach, the site condition index scores developed from this model resulted in a sigmoid logistic decay function that produced two threshold conditions between light and intermediate disturbance, and intermediate to heavy disturbances. Whereby, small amounts or infrequent disturbances have cumulative negative affects that reduce diversity away from “pristine" conditions. The rates of decline in species diversity (species loss) are eventually reduced (as indicated by the curve inflection), whereby only those species suited to the disturbance or combinations of disturbance persist. In many ways these patterns are consistent with hypotheses associated with the theories associated with intermediate disturbance. With continued degrading disturbance a gradual decline of species richness and ecosystem function is evident until the affects of disturbance become so great that the ecosystem dissembles. At this inflection rapid loss of species and biological activity is evident and the area losses the ability to recover from additional disturbance as well as previous disturbance. Loss of ecosystem activity would include biological storage capacity, biological processing of chemical material, and lost capacity to regulate water and chemical movement. Under these conditions, physical processes dominate the landscape and local surface and sub-surface erosion cascades into landscape scale problems. Further, as the second inflection is approached the likelihood of self-sustainability, and the self-replicated return to the original or desired condition, becomes less and less probabilistic without human investment. These findings are significant enough that they should be validated by a comparable study that reflects a continuum of current and past disturbances, as opposed to characterizing disturbance classes.

Though discrimant analysis and discriminant function analysis identified eight of the "Ecological Indicator Guilds" as being statistically functional, some interpretation questions are apparent. The primary issue is that discriminant analysis is designed to characterize along a multivariate continuum of points, preferably consisting of independent n-dimension axes. Interpretation of the results therefore becomes limited by the *a priori* information used to select and define disturbance "groups." Hence, a pessimistic view might suggest that discriminant analysis simply concurred that the investigator was in fact capable of defining and identifying disturbance classes. Further, no mention is made relative to the analysis or consideration that inherent correlation between parameters and ecological indicator guilds existed; such analysis could be made using path analysis to defract and represent these relationships. In support of the investigators, the intent of the phase I research was to reduce the number of potential ecological indicators and further investigate the collective response of those found to be worth while and then identify thresholds of change that could be directly related to a particular training event, feature, or condition. Thus, functional causality at closely defined intervals was expected to be developed, with continued improvement in interpretation.

Though often viewed as a continuum of disturbance from areas of no disturbance to highly disturbed training areas, in reality the landscape is a matrix of combinations of varying frequencies of four general types; soil disturbed (with and without compaction), and vegetation disturbed (with and without soil disturbance) at four conditions (recovered/undisturbed, recently disturbed, recovering, near recovered). As the proportions of these groupings change on the landscape, as subjugated by recovery process rates, our interpretation changes though artifacts of disturbance persist (e.g., seed banks that favor early successional species). Further, human disturbance, like entropy, tends to follow common paths; hence, training tends toward existing "corridors" away from canopy trees, slopes, and low lying wetland transitions. Further, logging and burning operations tend to track similar trails that parallel hardwood transitions and favor repeated-use corridors. These corridors often continue to degrade and widen, then in the absence of obstruction, braid into multiple common-use paths that slowly converge as biological inertia associated with vegetation re-establishment and rhizosphere reconditioning is lost. This leads to an important issue related to monitoring, namely what should be monitored; areas that have already been lost and will require restructuring through engineered solutions, areas that are less likely to be disturbed (e.g., within "groves" of trees), or intermediate positions near and distant from existing trails are most likely to become used as paths.

Table 9. Statistical significance of proposed metrics/indicators.

SEMP Researcher Proposed Metric	Ecological Indicator Phase I & II Evaluation	Statistical Significance (P) (Based on Simple Linear Regression)
Soil A-Horizon Depth	**A-Horizon Depth**	<0.001
Soil Compaction	**Soil Compaction**	<0.001
Soil-Sediment Carbon	**Soil Organics** Microbial Biomass Carbon	<0.001 0.006
Soil-Sediment Nitrogen	Ammonium (NH_4^+) Nitrate (NO_3^-)	0.66 0.038
Surface Cover (satellite)	**NDVI**[1]	<0.001
Canopy Cover	**Canopy Cover**	<0.001
Vegetation Structure	**Basal Area** **Tree Density** **Litter Cover**[2] Total Ground Cover	<0.001 <0.001 <0.001 0.21
Species Composition	Not Evaluated (requires taxonomic expertise by land manager)	-----

Relative to natural patterns of disturbance within the longleaf pine ecosystem, Platt et al (2003) found that disturbance intensity (fire) and variation in effects tends to be greatest nearest to tree bases. These patterns were attributed to differences in fuel amount (needles, bark, branches) at or near the base of individual trees. The result is greater spatial opportunities tend to develop at or near the base of trees in a fire disturbed regime, while in a military training disturbance regime, these opportunities tend to greatest away from tree-base microsites, the end result is this may affect seedling survival of particular species differently, which could have long-term implications towards forecasting compositional criteria for evaluating DFC's targets (e.g., annual grasses should be expected to be more abundant due to greater establishment opportunities in military training landscapes).

Like most public lands, it is likely that much of Fort Benning lands are near the first inflection, while other more concerning areas are at or near the second curve inflection. With multiple land-use needs, the first inflection should be considered as a "target" condition for most training areas. The inflection point would be desirable because reduced disturbance would allow for gradual recovery toward "pristine" conditions and continued or increased disturbance would be slightly buffered against complete loss of ecosystem function through the persistence of the remaining species and conditions. The usefulness of this concept is limited by background knowledge of each potentially occurring ecosystem associated with Fort Benning, namely what are "pristine" conditions and when do these inflections occur and what are the indicators. Further, most landscape settings various alternative habitat conditions, that are similarly suitable and stable, exist at the local scale (e.g., upland hardwood forest, pine savanna, open range, intermediate combinations). Collectively, the proportion and distribution of these various habitats have influence over installation-wide processes associated with water and air quality as well as overall habitat suitability for populations of species.

Journal articles

Published

Duda, J.J., D.C. Freeman, M.L. Brown, J.H. Graham, A.J. Krzysik, J.M. Emlen, J.C. Zak, and D.A. Kovacic. 2003. Estimating disturbance effects from military training using developmental instability and physiological measures of plant stress. Ecological Indicators 3:251-262.

Freeman, D.C., M.L. Brown, J.J. Duda, J.H. Graham, J.M. Emlen, A.J. Krzysik, H.E. Balbach, D.A. Kovacic, and J.C. Zak. 2004. Developmental instability in Rhus copallinum L.: multiple stressors, years, and responses. International Journal of Plant Sciences. 165(1):53-63.

Freeman, D.C., M.L. Brown, J.J. Duda, J.H. Graham, J.M. Emlen, A.J. Krzysik, H.E. Balbach, D.A. Kovacic, and J.C. Zak. 2004. Photosynthesis and fluctuating asymmetry as indicators of plant response to soil disturbance in the Fall Line Sandhills of Georgia: a case study using Rhus copallinum and Ipomoea pandurata. International Journal of Plant Sciences. 165(5): 805-816.

Freeman, D.C., M.L. Brown, J.J. Duda, J.H. Graham, J.M. Emlen, A.J. Krzysik, H.E. Balbach, D.A. Kovacic, and J.C. Zak. 2005. Leaf fluctuating asymmetry, soil disturbance and plant stress: a multiple year comparison using two herbs, Ipomoea pandurata and Cnidoscolus stimulosus. Ecological Indicators 5:85–95.

Graham, J.H., H.H. Hoyt, S. Jones, K. Wrinn, A.J. Krzysik, J.D. Duda, C.D. Freeman, J.M. Emlem,T J. C. Zak, D.A. Kovacic, C. Chamberlin-Graham, and H.E. Balbach. 2004. Habitat disturbance and the diversity and abundance of ants (Formicidae) in the Fall-Line Sandhills of Georgia. Journal of Insect Science. 4:15-30.

Sobek, E.A., and J.C. Zak. 2003. The soil FungiLog procedure: methods and analytical approaches towards understanding fungal functional diversity. Mycologia 95:590-602.

Submitted

Freeman, D.C., M.L. Brown, J.J. Duda, S. Kitchen, J.M. Emlen, J.H. Graham, J. Malol, E. Bankstahl, A.J. Krzysik, H.E. Balbach, D.A. Kovacic, and J.C. Zak. A multiple year study of the influence of disturbance and prescribed fires on the growth and development instability of loblolly pine (Pinus taeda) in the Fall-Line Sandhills of Georgia. Oecologia. (Submitted April 2005) (In Revision March 2006)

Graham, J.H., A.J. Krzysik, D.A. Kovacic, J.J. Duda, D.C. Freeman, J.M. Emlen, J.C. Zak, W.R. Long, M.P. Wallace, C. Chamberlin-Graham, J. Nutter, and H.E. Balbach. Intermediate disturbance and ant communities in a forested ecosystem. Diversity and Distributions. (Submitted December 2005)

Kovacic, D.A., A.J. Krzysik, M.P. Wallace, J.C. Zak, D.C. Freeman, J.H. Graham, H.E. Balbach, J.J. Duda, and J.M. Emlen. Soil mineralization potential as an ecological indicator of forest disturbance. Ecological Indicators or Biology and Fertility of Soils (Submitted March 2006).

Technical reports

Published

Krzysik, A.J., and H.E. Balbach. 2007. Development of a Site Comparison Index: Southeast Upland Forests. ERDC/CERL TR-07-12. U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory, Champaign, IL.

Submitted

Krzysik, A.J., H.E. Balbach, J.J. Duda, J.M. Emlen, D.C. Freeman, J.H. Graham, D.A. Kovacic, L.M. Smith, and J.C. Zak. Development of Ecological Indicator Guilds for Land Management. Draft Final SERDP Technical Report. (Submitted April 2005)

SEMP Project CS-1114C-99: Indicators of ecological change (PI: V. Dale, Oak Ridge National Laboratory Overview of indicator characteristics)

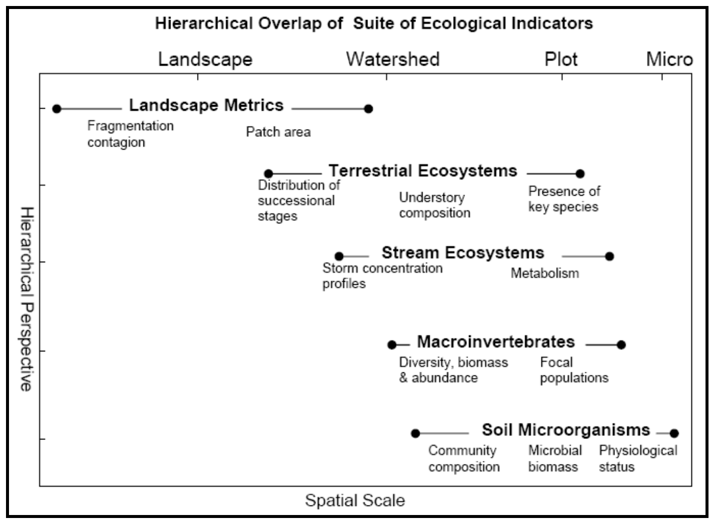

Figure 37. Hierarchical overlap of suite ecological indicators.

The initial aspect of this study was to fully consider the assumptions, values, and limitations to using ecological indicators to track wanted and unwanted affects of land-use and land-management at various scales. Three concerns that limit the use of indicators as a management tool:

Management and monitoring programs often depend on a small number of indicators and, as a consequence, fail to consider the full complexity of the ecological system.

Choice of ecological indicators is often confounded by management programs that have vague management goals and objectives.

Management and monitoring programs often lack scientific rigor because of their failure to use a defined protocol for identifying ecological indicators.

Development of a procedure for ecological indicator selection that is based on a hierarchical framework and grounded in clear management goals will address concerns associated with the subjective and disorganized methods often used. The ultimate goal is to establish the use of ecological indicators as a means for including ecological objectives and concerns in management decisions.

Selection of effective indicators is important for the overall success of any monitoring program. In general, ecological indicators need to capture the complexities of the ecosystem yet remain simple enough to be easily and routinely monitored. The authors suggest that ecological indicators meet the following criteria:

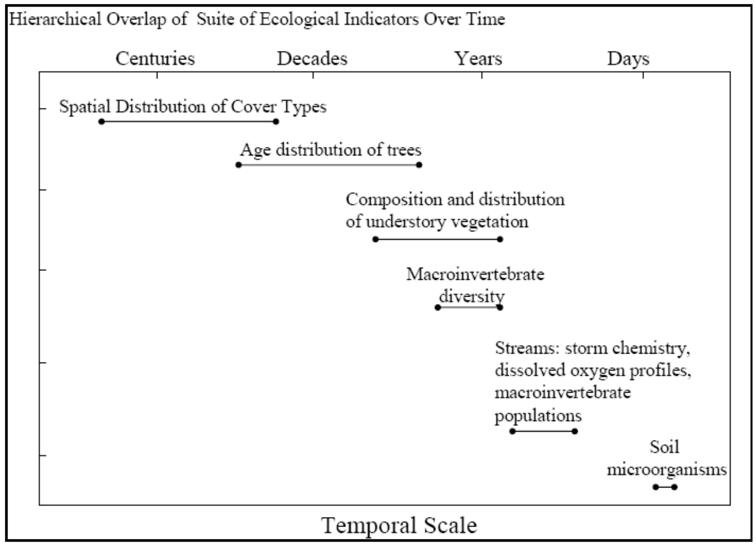

Figure 38. Hierarchical overlap of suite ecological indicators over time.

- Be easily measured, understood, and cost-effective.
- Be sensitive to stresses on the system.
- Respond to stress in a predictable manner.
- Signify an impending change in key characteristics of the ecological system.
- Predict changes that can be averted by management actions.
- Integrative or correlative across key ecological gradients and scales.
- Have a known response to disturbances, anthropogenic stresses, and changes over time.
- Have low variability in response.

Analysis of potential landscape indicators

In addition to prioritizing land management goals and to develop land management targets, coverage of existing vegetation and habitat can be used to estimate broadscale species suitability patterns as well as to estimate resource-use, resource-pools, and resource sustainability.

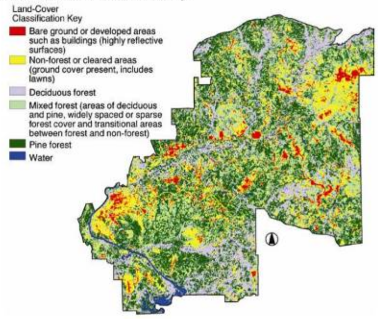

Fig. 4. Land-cover classification for Fort Benning, Georgia, based on ETM+ imagery for 1999.

Figure 39. Land cover classification for Fort Benning, GA, based in ETM+ imagery for 1999.

Table 10. Metrics for entire landscape at Fort benning, GA.

Since settlement, patterns of habitat patch size and predisposition have been greatly altered by the effects of compounding differences in land-use. These changes in landscape patterns are thought to have altered species patterns as much as changes in habitat quality.

Table 3. Metrics for entire landscape at Fort Benning, GA

Year	Total edge with border (km)	Number of patches	Patch density	Largest patch index
1827	6624	131	0.1774	73.5166
1974	49405	61312	115.0106	0.0581
1983	48498	61256	114.9055	0.0628
1991	52672	62254	116.7626	0.0351
1999	93360	61837	115.9954	0.0304

This research examined landscape indicators that signal ecological change in both intensely used and lightly used lands at Fort Benning. Changes in patterns of land cover through time affect the ecological system by altering the proportion and distribution of habitats for species that these cover types support. This analysis of landscape pattern began with a landscape characterization based on witness tree data from 1827 and the 1830s and remotely sensed data from 1974, 1983, 1991, and 1999. The focus was changes associated with five cover types (bare/developed land, deciduous forest, mixed forest, pine forest, and nonforest vegetated land). The most appropriate and useful metrics for these comparisons were; percent cover, total edge (km), number of patches, descriptors of patch area, nearest neighbor distance, mean perimeter-to-area ratio, shape range, and clumpiness. These parameters are ecologically important because they influence the interactions of individuals and populations at the landscape level and help define the capacity and quality of ecological communities.

Analysis of potential watershed indicators

Watershed scale indicators were studied using twelve 2nd- and 3rd-order streams. Stream quality, based on parameters discussed below, was then compared to various watershed attributes (% forest coverage, # roads, etc.). This study found that the best indicator of watershed disturbance is the sum of the proportion of bare ground on slopes >3% and unpaved road cover within each drainage area. Study streams drained watersheds ranging in disturbance from about ~2 to 14%. Overall, historic land use explained more variation in contemporary bed stability and longer-lived, low-turnover taxa than contemporary land use, suggesting a "legacy" effect on these stream measures.

Past land conditions such as pre- or early European settlement era's are commonly used to estimate past habitats, their proportions, and ultimately to develop desired future conditions. This information can also be used to prioritize land management activities, either by area or existing "representitiveness".

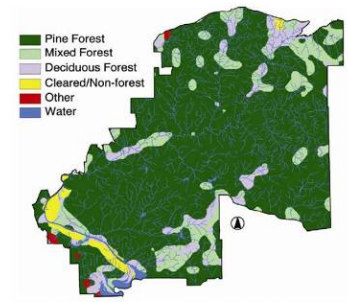

Figure 3. Land cover map for Fort Benning in 1827

Map based on land survey data

Figure 40. Land cover map for Fort Benning in 1827.

Physical

1. Physical features such as hydrologic flashiness (based on 4-hour storm flow recession constants) and bed stability were significantly impacted by disturbance level. Greater disturbance equates to reduced watershed holding capacitance thus greater variation in water flow; thus, reduced stability of bed sediments.
2. Stream channel organic variables, such as the amount of benthic particulate organic matter (BPOM) and coarse woody debris (CWD), were highly related to watershed disturbance.
3. Concentrations of total and inorganic suspended sediments during base flow and storm periods were excellent indicators of disturbance, increasing with increasing disturbance levels. The rate of increase accelerates when watershed disturbance exceeds 10-12%.
4. Base flow concentrations of dissolved organic carbon (DOC) and soluble reactive phosphorus were good disturbance indicators, declining with increasing disturbance levels.

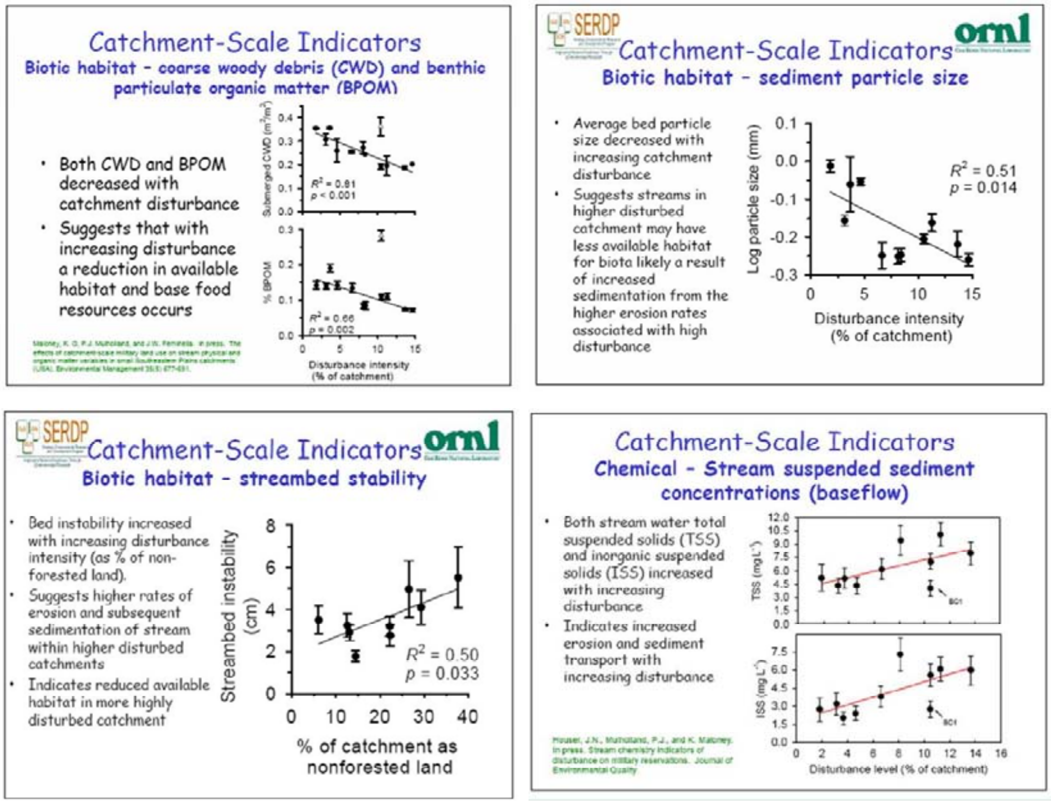

Figure 41. Catchment-scale indicators.

Biological

1. Stream benthic macroinvertebrates were good biological indicators of watershed-scale disturbance. Measures such as stream macro-invertebrate community richness (e.g., number of Ephemeroptera, Plecoptera, and Trichoptera [EPT] taxa and richness of Chironomidae) negatively corresponded with watershed disturbance; however, except for chironomid richness, all measures showed high variation among seasons and annually. It should be noted that in other stream systems Chironomid (midge flies) diversity is highest in “moderate to good quality” streams as opposed to “pristine quality” streams.
2. The Georgia Stream Condition Index [GASCI] consistently indicated watershed disturbance; with low seasonal and inter-annual variation. This work, and other SERDP funded work, has led to modifications and improvements of this measure and its interpretability. These protocol are now deployed as part of the stream monitoring program.
3. The proportional abundance of the two dominant fish species, broadstripe shiner (*Pteronotropis euryzonus*) and dixie chub (*Semotilus thoreauianus*), were strongly associated with disturbance. Abundance of *P.*

euryzonus and *S. thoreauianus* was negatively and positively related to disturbance, respectively.

Analysis of potential plot-level indicators

Vegetation indicators

1. Heavy disturbance reduces canopy cover and understory cover in upland pine habitats, and results in different composition. Relative to reference sites, sites with intermediate levels of disturbance had slightly less canopy and understory cover, but continued differences in species composition and diversity. Low disturbance or protected sites tend to support higher species diversity and are composed of species with high habitat fidelity.

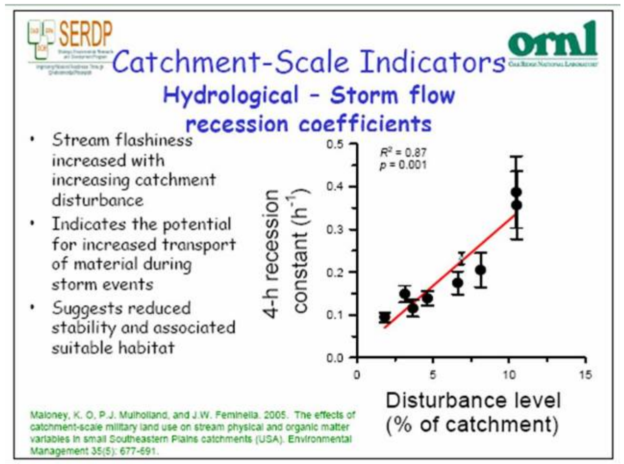

Figure 42. Catchment-scale indiocators — storm flow recession coefficients.

2. Disturbance intensity is reflected by patterns of understory species cover, but due to limited species fidelity, better reflected by life form patterns. Heavy training tends to favor therophytes (annuals) as well as tolerant chamaephytes (buds above ground) and cryptophytes (bulb plants), and heavy disturbance disfavors phanerophytes (trees, tall shrubs) and hemicryptophytes (bud at ground level) abundance. Typically, fire-maintained upland pine habitats are dominated

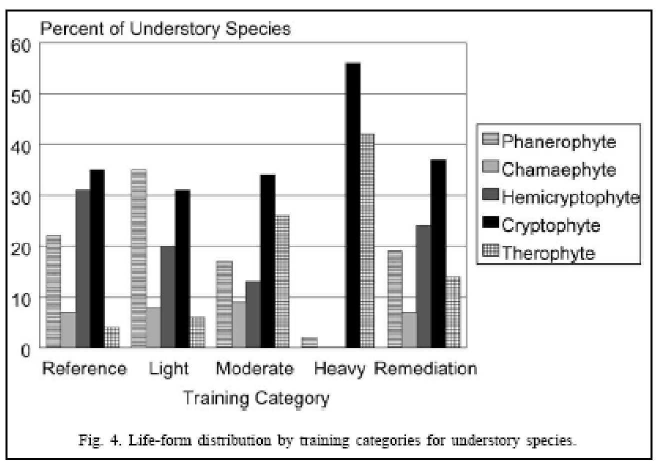

Figure 43. Life-form distribution by training categories for understory species.

by phanerophytes (longleaf pine), chamaephytes (perennial grasses and forbs), and because of periodic burning, scattered occurrences of other life forms.

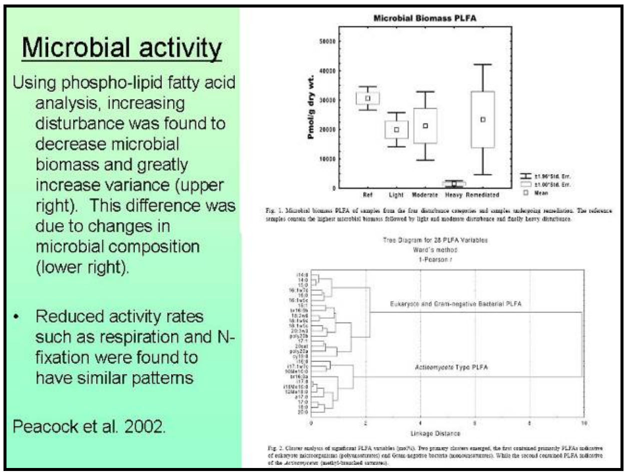

Figure 44. Microbial activity.

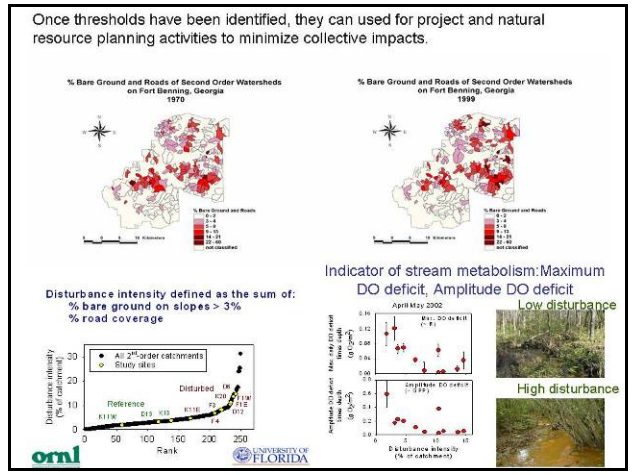

Figure 45. Identified thresholds can be used for project and natural resource planning activites to minimize collective impacts.

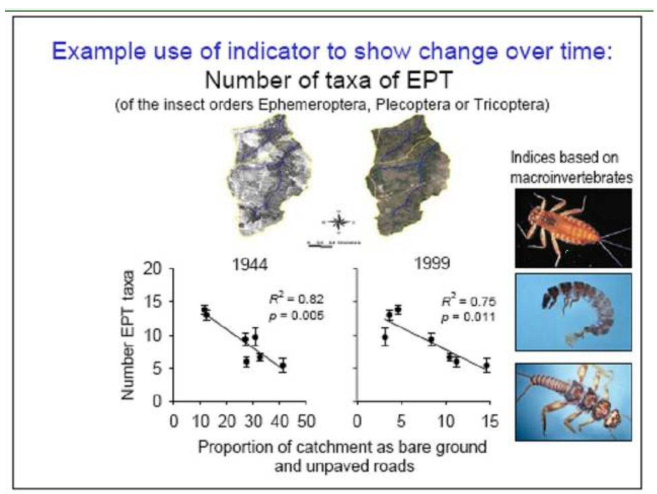

Figure 46. Example use of indicator to show change over time.

3. Analysis of soils collected from each transect revealed that depth of the A layer of soil was significantly higher in reference and light training areas which may explain the life form distributions. In addition, the diversity of plant families and, in particular, the presence of grasses and composites were indicative of training and remediation history. These results are supported by prior analysis of life form distribution subsequent to other dis-

turbances and demonstrate the ability of life form and plant families to distinguish between military disturbances in longleaf pine forests.

Microbial indicators

1. Using the soil microbial biomass and rhizosphere community composition as ecological indicators, reproducible changes showed increasing training disturbance decreases soil viable biomass, biomarkers for microeukaryotes and Gram-negative bacteria, while increasing the proportions of aerobic Gram-positive bacterial and *actinomycete* (fungi) biomarkers. Other SEMP studies found similar relationships associated with rhizosphere community composition and disturbance. The balance between bacterial and fungal markers is significant because both groups differ in efficiency of nutrient cycling and storage.
2. Indicators of rhizosphere activity, such as phospholipid fatty acids (PLFA), differed significantly with land usage, and when modeled, could be used to discriminate disturbance into four groups with roughly 2/3 of the locations correctly classified. Indicators of rhizosphere activity are seasonally and spatially variable and for proper interpretation may require additional soil variables to be sampled.

Collective overview of plot-level indicators

Similar to the SEMP study findings of Krzysik et al., combinations of indicators can be used to explain variation between plots; hence, provide a post-priori assessment of the status of terrestrial conditions at various levels. Again, these indicators (see latter section for Integration Project Review) are significantly correlated and through path analysis independent contributions of particular indicators to the collective solution could be "tweezed" out to further reduce the list of potential indicators for monitoring. ORNL found that ten indicators could be used to explain 90% of the variation among plots from five different military-use levels.

Road and vehicle impacts at different scales at Fort Benning

Tracked vehicle experimentation indicates that the upper soil profile is compacted and will likely persist in a compacted state for an extended period. Vegetation is initially lost but begins to recover within a year. Compositional changes persist following recovery, more importantly the post-disturbance group tends to have shallow root profiles relative to those species lost through disturbance.

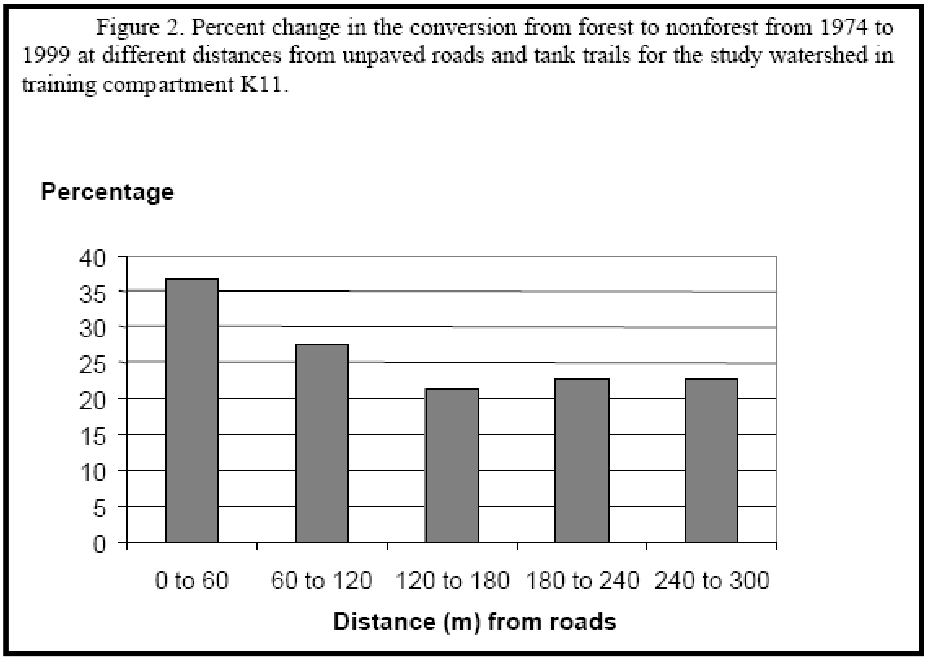

Figure 47. Percent change in the conversion from forest to nonforest from 1974 to 1999 at different distances from unpaved roads and tank trails for the study watershed in trainng compartment K11.

Local patterns of trail use suggest that trails expand to about twice the width of the most commonly used trail vehicle. Convergence and mergers of adjacent trails lead to expanded disturbance patterns with periodic establishment of new "pioneer" trails. "Pioneer" trails then expand and become unvegetated corridors. Trail frequencies are greatest along upper slope and ridge positions. In areas with similar disturbance intensity, trail densities are more in flat areas. Finally, trails tend to avoid large trees and favor previously disturbed areas.

At the watershed and installation scale, it was determined through GIS analysis that most vegetation loss is associated with unpaved roads and trails. Not surprisingly, patterns and density of unpaved roads and trails reflect use intensity. Regionally, conversion from forested to unforested conditions is correlated with urban expansion along paved road corridors.

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SEMP Project CS-1114D-00: Disturbance of soil organic matter and nitrogen dynamics: implications for soil and water quality (PI: C. Garten, Oak Ridge National Laboratory)

This project identified five objectives and they are listed as follows; a) Effect of Land Use and Disturbance on Soil Quality, b) Disturbance Thresholds to Ecosystem Recovery, c) Model Predictions of Soil Organic Matter for Different Land Cover Types, d) Contribute to and Conduct Field Experiments on Ecosystem Disturbance, and e) Analyze Spatial Patterns of Soil Carbon and Nitrogen for the Purpose of Predicting Potential Non-Point Nitrogen Sources on the Landscape.

Effect of land use and disturbance on soil quality

The objective of this task was to discern and investigate the effects of soil disturbance on key indicators of soil quality at Fort Benning, Georgia. Military activities at Fort Benning that result in soil disturbance include various mounted and dismounted activities that involve infantry, artillery, wheeled, and tracked vehicle training. Soil samples were collected along a disturbance gradient that included: (1) relatively undisturbed reference sites, (2) light military use, (3) moderate military use, (4) heavy military use, and (5) remediated sites. The most significant findings were:

1. Consistent with other SEMP studies, with the exception of surface soil bulk density, measured soil properties at reference and light use sites were similar. Relative to reference sites, greater surface soil bulk density (Table 11, top), lower soil carbon concentrations (Table 11, middle), and less carbon and nitrogen in particulate organic matter (POM) were found at moderate use, heavy use, and remediated sites (Table 11, bottom).

Table 11. Mean values for surface (0–20 cm) soil bulk density, carbon concentrations, carbon stocks, and soil C:N ratios under various disturbacne categories at Fort Benning, GA.

Table 1
Mean values for surface (0–20 cm) soil bulk density, carbon concentrations, carbon stocks, nitrogen stocks, and soil C:N ratios under various disturbance categories at Fort Benning, Georgia

Variable	Disturbance category				
	RF	LU	HU	MU	RM
Soil bulk density (g cm^{-3})	1.25^{a} (0.09)	1.38^{b} (0.10)	1.53^{c} (0.08)	1.51^{c} (0.06)	1.51^{c} (0.06)
C concentration (%)	0.92^{a} (0.35)	0.98^{a} (0.50)	0.17^{b} (0.44)	0.56^{c} (0.46)	0.55^{c} (0.33)
C stock (mg C cm^{-2})	226^{a} (0.30)	260^{a} (0.42)	53^{b} (0.46)	167^{c} (0.42)	164^{c} (0.30)
N stock (mg N cm^{-2})	$6.11^{a,b}$ (0.24)	7.70^{a} (0.38)	5.03^{b} (0.39)	7.93^{a} (0.41)	$6.24^{a,b}$ (0.68)
Soil C:N ratio	38.8^{a} (0.38)	34.0^{a} (0.18)	12.8^{b} (0.68)	21.8^{c} (0.33)	31.7^{a} (0.39)

Coefficients of variation are in parenthesis. Mean values in the same row with different alphabetic superscripts are significantly different. Sample size is 15 for each mean (except those under RM where $n = 10$). RF: reference site; LU: light military use; HU: heavy military use; MU: moderate military use; RM: remediated site.

Table 2
Mean sand fraction, and fraction of carbon and nitrogen in particulate organic matter (POM) and mineral-associated organic matter (MOM) in surface (0–20 cm) soils from different disturbance categories at Fort Benning, Georgia

Variable	Disturbance category				
	RF	LU	HU	MU	RM
Sand fraction (≥53 μm)	0.77^{a} (0.09)	0.83^{a} (0.05)	0.83^{a} (0.10)	0.85^{a} (0.07)	0.83^{a} (0.01)
Fraction POM-C	0.44^{a} (0.10)	$0.43^{a,b}$ (0.14)	0.19^{c} (0.47)	0.18^{c} (0.35)	$0.31^{b,c}$ (0.08)
Fraction MOM-C	0.56^{a} (0.08)	$0.57^{a,b}$ (0.10)	0.81^{c} (0.11)	0.82^{c} (0.08)	$0.69^{b,c}$ (0.03)
Fraction POM-N	0.28^{a} (0.30)	0.28^{a} (0.53)	0.00^{b} (0.00)	0.04^{b} (1.26)	0.05^{b} (0.70)
Fraction MOM-N	0.72^{a} (0.12)	0.72^{a} (0.20)	1.00^{b} (0.00)	0.96^{b} (0.06)	0.95^{b} (0.04)

Coefficients of variation are in parenthesis. Means in the same row with different alphabetic superscripts are significantly different. Sample size is 3 for each mean (except those under RM where $n = 2$). RF: reference site; LU: light military use; HU: heavy military use; MU: moderate military use; RM: remediated site.

Table 3
Soil carbon and nitrogen in particulate organic matter (POM) and mineral-associated organic matter (MOM), refractory soil carbon (determined by acid–base digestion), and corrected POM-C (adjusted for refractory soil carbon) in surface (0–20 cm) mineral soils from different disturbance categories at Fort Benning, Georgia

Variable	Disturbance category				
	RF	LU	HU	MU	RM
POM-N (mg POM-N g^{-1} soil)	0.083^{a} (0.32)	0.072^{a} (0.54)	0.0^{b}	0.016^{b} (1.32)	0.009^{b} (0.75)
MOM-N (mg MOM-N g^{-1} soil)	0.21^{a} (0.10)	$0.20^{a,b}$ (0.45)	0.08^{c} (0.28)	0.27^{a} (0.21)	$0.15^{b,c}$ (0.04)
Uncorrected POM-C (mg POM-C g^{-1} soil)	4.25^{a} (0.34)	4.11^{a} (0.24)	0.35^{b} (0.54)	1.15^{b} (0.44)	1.51^{b} (0.21)
Refractory C (fraction)	0.36^{a} (0.19)	0.37^{a} (0.21)	0.67^{a} (0.57)	0.37^{a} (0.60)	0.33^{a} (0.14)
Corrected POM-C (mg POM-C g^{-1} soil)	2.67^{a} (0.24)	2.62^{a} (0.28)	0.16^{b} (1.21)	0.76^{b} (0.63)	1.02^{b} (0.28)
MOM-C (mg MOM-C g^{-1} soil)	5.35^{a} (0.27)	5.70^{a} (0.39)	1.42^{b} (0.32)	4.96^{a} (0.02)	$3.34^{a,b}$ (0.10)
Refractory C (mg C g^{-1} soil)	1.58^{a} (0.53)	1.49^{a} (0.32)	0.19^{b} (0.48)	0.39^{b} (0.40)	0.49^{b} (0.07)

Coefficients of variation are in parenthesis. Means in the same row with different alphabetic superscripts are significantly different. Sample size is 3 for each mean (except those under RM where $n = 2$). RF: reference site; LU: light military use; HU: heavy military use; MU: moderate military use; RM: remediated site.

2. Studies along a pine forest chronosequence indicated that carbon stocks in POM gradually increased with stand age (Figure 48). An analysis of soil C:N ratios, as well as soil carbon concentrations and stocks, indicated a recovery of soil quality at moderate military use and remediated sites relative to heavy military use sites. These results indicate that measurements of soil carbon and nitrogen are ecological indicators that can be used by military land managers to identify changes in soil from training activities and to rank training areas on the basis of soil quality (Garten et al., 2003).

Land cover characterization might also help land managers assess the impacts of management practices and land cover change on attributes linked to the maintenance and/or recovery of soil quality. However, connections between land cover and measures of soil quality are not well established, but critically necessary to effectively link soil condition, site productivity and capacity, and landscape imagery. Though direct relationships are desirable, strong correlative relationships with known distributions can be used to effectively forecast response and condition. We examined differences in soil carbon and nitrogen among various land cover types at Fort Benning, Georgia. Forty-one sampling sites were classified into five major land cover types: deciduous forest, mixed forest, evergreen forest or plantation, transitional herbaceous vegetation, and barren land.

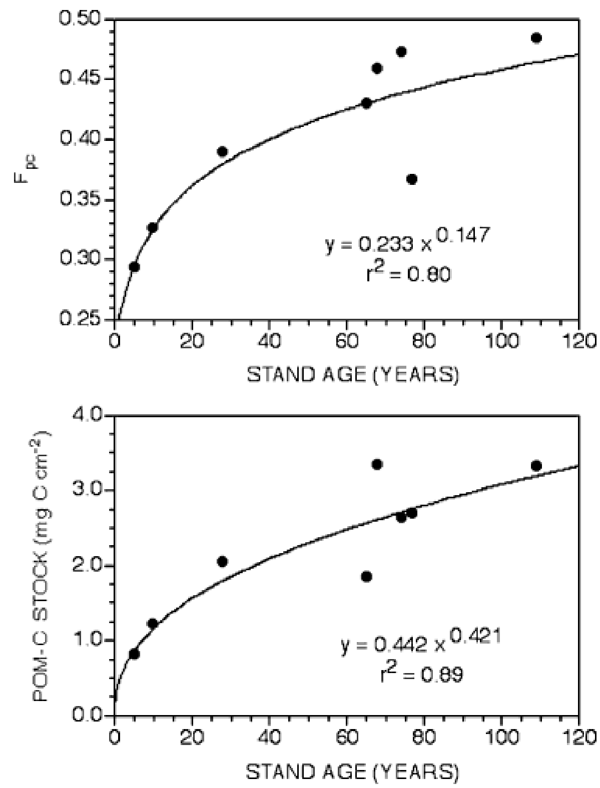

Fig. 1. Above: relationship between the fraction of POM carbon in surface (0–20 cm) mineral soil (F_{pc}) and forest stand age along a chronosequence of reference, light military use, and remediated sites at Fort Benning, Georgia. Below: relationship between the stock of POM carbon (corrected for refractory soil C) in surface mineral soil and forest stand age at the same sites.

Figure 48. (Above) relationship between the fraction of POM carbon in surface (0–20 cm) mineral soil (F_{pc}) and forest stand age along a chronosequence of reference, light military use, and remediated sites at Fort Benning, GA; (below) relationship between the stock of POM carbon (corrected for refractory soil C) in surface mineral soil and forest stand age at the same sites.

1. Key measures of soil quality (including mineral soil density, nitrogen availability, soil carbon and nitrogen stocks, as well as properties and chemistry of the O-horizon) were significantly different among the five land covers.

2. In general, barren land had the poorest soil quality. Barren land, created through disturbance by tracked vehicles and/or erosion, had significantly greater soil density and a substantial loss of carbon and nitrogen relative to soils at less disturbed sites.
3. It was estimated that recovery of soil carbon under barren land at Fort Benning to current day levels under transitional vegetation or forests would require about 60 years following reestablishment of vegetation.
4. Maps of soil carbon and nitrogen were produced for Fort Benning based on a 1999 land cover map and field measurements of soil carbon and nitrogen stocks under different land cover categories (Garten and Ashwood, 2004a). These maps show patterns that reflect topo-edaphic conditions and past land-use.

Experimental patterns from ecosystem disturbance

As expected and comparable to findings by the Univ. of Florida SEMP group, soil density was less at riparian sites, but riparian soils had significantly greater carbon and nitrogen concentrations and stocks than upland soils. Most of the carbon stock in riparian soils was associated with mineral-associated organic matter (i.e., the silt + clay fraction physically separated from whole mineral soil).

Topographic differences in soil nitrogen availability were highly dependent on the time of sampling. Riparian soils had higher concentrations of extractable inorganic nitrogen than upland soils and also exhibited significantly greater soil nitrogen availability during the spring sampling. Riparian settings are also likely to have a much higher demand for nitrogen, suggesting an even larger difference in availability between systems.

Table 12. Mean (±SE) O-horizon properties at upland sites disturbed by a bulldozer and at paired, undisturbed (control) sites in K-11. The numbe of sampling stations is shown inparenthesis).

Measurement	Treatment: Control (n = 14)	Treatment: Disturbed (n = 14)	Mean difference	Paired t-value
Dry mass (g cm^{-2})	640 ±57	257 ±112	-384	3.26**
C concentration (%)	47.8 ±0.9	36.7 ±1.5	-12.9	9.19***
C:N ratio	100.5 ±7.5	73.5 ±8.7	-36.2	4.5**
C stock (g C m^{-2})	310 ±30	91 ±38	-219	4.9***
N stock (g N m^{-2})	3.19 ±0.34	1.39 ±0.60	-1.81	2.9*

*$P \leq 0.05$; **$P \leq 0.01$; ***$P \leq 0.001$

Through direct study involving bulldozer impacts, O-horizon dry mass and carbon stocks were significantly reduced by tracked vehicle movement, relative to undisturbed sites, and there was an indication of reduced mineral soil carbon stocks in the disturbance zone (Table 13). The latter finding is consistent with SREL SEMP observations.

Differences in the surface (0-10 cm) mineral soil also indicated a significant increase in soil density as a result of disturbance by the bulldozer (Table 12). Although there was some tendency for greater soil nitrogen availability in disturbed soils, the changes were not significantly different from undisturbed controls. It is expected that repeated soil disturbance over time, which will normally occur in a military training area, would simply intensify the changes in soil properties that were measured following a one-time soil disturbance at the K-11 training compartment.

Table 13. Mean (±SE) carbon stocks (g C m^2) in particulate organic matter (POM-C), mineral associated organic matter (MOM-C), a refractory part of POM (REF-C), and surface mineral soil (0–20 cm) under different land covers at Fort benning GA.

Soil carbon fraction	Land cover category			F-value
	Barren	Transitional land	Forest	
POM-C	73[a] ±26	462[b] ±75	474[b] ±53	9.9 ($P < 0.001$)
MOM-C	421[a] ±157	1790[b] ±236	1716[b] ±132	14.2 ($P < 0.001$)
REF-C	34[a] ±19	297[b] ±54	247[b] ±45	4.8 ($P < 0.05$)
Total	529[a] ±197	2548[b] ±257	2433[b] ±169	19.9 ($P < 0.001$)

* Means in the same row with different alphabetic superscripts are significantly different

The experiment was also useful for identifying soil measurements that are particularly sensitive to disturbance and therefore can be used successfully as indicators of a change in soil properties as a result of heavy, tracked-vehicle traffic at Fort Benning.

Measurements related to total O-horizon mass and carbon concentrations or stocks exhibited changes that ranged from ˜25 to 75% following the one-time disturbance.

Changes in surface (0-10 cm) mineral soil density or measures of surface soil carbon and nitrogen following the disturbance were less remarkable and ranged from ˜15 to 45% (relative to undisturbed controls).

Table 14. Mean (±SE) soil density (g cm^2) under differnet land cover categories at Fort benning, GA.*

Soil depth (cm)	Land cover category: Barren	Transitional land	Evergreen forest	Mixed forest	Deciduous forest	F-value†
0-10	1.64[a] ±0.02	1.37[b] ±0.06	1.32[b] ±0.06	1.16[c] ±0.04	1.10[c] ±0.04	18.5 ($P < 0.001$)
10-20	1.71[a] ±0.03	1.60[ab] ±0.05	1.43[bc] ±0.10	1.34[c] ±0.06	1.34[c] ±0.05	6.1 ($P < 0.001$)
20-30	1.72[a] ±0.03	1.61[ab] ±0.08	1.52[bc] ±0.09	1.36[bc] ±0.08	1.41[c] ±0.04	4.4 ($P < 0.01$)
30-40	1.68[a] ±0.03	1.57[ab] ±0.09	1.60[ab] ±0.06	1.39[b] ±0.08	1.47[b] ±0.06	2.7 ($P < 0.05$)

* Means in the same row with different alphabetic superscripts are significantly different
† degrees of freedom (df) = 4,36 for each F-value, except 30-40 cm where df = 4,33

Soil nitrogen availability (measured as initial extractable soil nitrogen or nitrogen production in laboratory incubations) was the least sensitive and the least useful indicator for detecting a change in soil quality. Collectively, the results suggest that the best indicators of a change in soil quality will be found at the soil surface because there were no statistically significant effects of bulldozer disturbance at soil depths below 10 cm (Garten and Ashwood, 2004).

Models for the Relationship of Disturbance, Ecological Processes, and Land-use Patterns

Disturbance threshold to ecosystem recovery

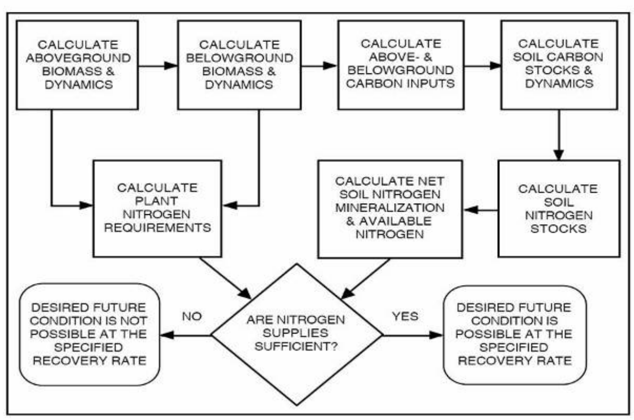

Fig. 1. Conceptual model and steps leading up to the nutrient threshold test in the spreadsheet model. The desired future condition is a target for aboveground standing crop biomass.

Figure 49. Conceptual model and steps leading up to the nutrient threshold test in the spreadsheet model. The desired future condition is a target for aboveground standing crop biomass.

The model calculates aboveground and belowground biomass, soil carbon inputs and dynamics, soil nitrogen stocks and availability, and plant nitrogen requirements. A threshold is crossed when predicted soil nitrogen supplies fall short of predicted nitrogen required for sustain biomass accrual at a specified recovery rate. Four factors were important to development of thresholds to recovery: (1) initial amounts of aboveground biomass (i.e., forest volume estimates),

(2) initial soil carbon stocks (i.e., soil quality), (3) relative recovery rates of biomass (i.e., forest growth rate), and (4) soil sand content (general estimate). Thresholds to ecosystem recovery predicted by the model identified the following findings:

Table 15. Mean (±SE) dry mass, carbon, and nitrogen concentrations and stocks, and ratios in the O-horizons under different land cover categories at Fort Benning, GA.

O-horizon property	Land cover category					F-valu
	Barren	Transitional land	Evergreen forest	Mixed forest	Deciduous forest	
Dry mass ($g\ m^{-2}$)	0.0^{a}	894^{b} ±474	1053^{b} ±123	1152^{bc} ±128	1821^{c} ±193	7.4 (P < 0.0
Carbon (%)	--	18.3^{a} ±2.2	40.1^{b} ±1.5	37.5^{c} ±1.6	30.2^{c} ±1.2	33.9 (P < 0.0
Nitrogen (%)	--	0.54^{a} ±0.05	0.54^{a} ±0.03	0.72^{b} ±0.02	0.79^{b} ±0.06	10.3 (P < 0.0
Carbon stock ($g\ C\ m^{-2}$)	--	136^{a} ±59	413^{b} ±39	422^{bc} ±37	536^{c} ±31	15.4 (P < 0.0
Nitrogen stock ($g\ N\ m^{-2}$)	--	5.3^{a} ±3.0	5.7^{a} ±0.8	8.3^{a} ±1.0	14.9^{b} ±2.4	5.1 (P < 0.(
C:N ratio	--	34.5^{a} ±4.2	76.5^{b} ±4.3	52.1^{c} ±2.3	39.9^{a} ±3.9	25.1 (P < 0.0

* Means in the same row with different alphabetic superscripts are significantly different

† df = 3,27 for each F-value, except for O-horizon dry mass where df = 4,36

5.

1. Initial soil carbon stocks influenced the predicted patterns of recovery by both old field and forest ecosystems. Low initial carbon stocks resulted in slowed initial recovery rates and greater potential for C:N imbalances.
2. Forests and old fields on soils with varying sand content had different predicted thresholds to recovery. Ecosystems associated with sandier soils had slightly higher recovery rates because of greater resilience of processes within sandy soils.
3. Soil carbon stocks at barren sites on Fort Benning generally lie below predicted thresholds to 100% recovery of desired future ecosystem conditions. This implies that without supplement, barren sites will have a prolonged period (decades) before full recovery.
4. Calculations with the model indicated that reestablishment of vegetation on barren sites to a level below the desired future condition is possible at recovery rates used in the model, but the time to 100% recovery of desired future conditions, without crossing a nutrient threshold, is prolonged by a reduced rate of forest growth.
5. Predicted thresholds to ecosystem recovery were less on soils with more than 70% sand content. This finding indicates that sandy soils, with the same level of observed disturbance, would recover more rapidly than a similar condition associated with clayey soils.
6. Similar to Collins' SEMP findings, the lower thresholds for old field and forest recovery on more sandy soils are apparently due to higher relative rates of net soil nitrogen mineralization in more sandy soils. Calculations with the model indicate that a combination of desired future conditions,

initial levels of soil quality (defined by soil carbon stocks), and the rate of biomass accumulation determines the predicted success of ecosystem recovery on disturbed soils (Garten and Ashwood, 2004).

Table 16. Mean (±SE) potential net soil notrogen mineralization (µN g^{-1} soil) during a 12-week aerobic laboratory incubation and potential net nitrification (µN g^{-1} soil) during the first 6 weeks (Phase 1) and the second 6 weeks (Phase 2) of aerobic laboratory incubations of surface (0–20 cm) mineral soil.

N production (µg N g^{-1} soil)	Land cover category					F-value
	Barren	Transitional land	Evergreen forest	Mixed forest	Deciduous forest	
Net soil N mineralization	1.79^{a} ±1.01	9.93^{bc} ±1.97	5.41^{ab} ±2.25	11.08^{bc} ±2.77	12.83^{c} ±1.80	4.8 ($P < 0.01$)
Net nitrification (phase 1)	1.01^{a} ±0.43	4.51^{b} ±1.45	1.05^{a} ±0.85	0.84^{a} ±0.53	1.43^{a} ±0.35	3.5 ($P < 0.05$)
Net nitrification (phase 2)	0.81^{a} ±0.70	5.56^{ab} ±1.10	3.42^{a} ±1.25	6.53^{b} ±2.42	9.60^{b} ±2.17	4.0 ($P < 0.01$)

* Means in the same row with different alphabetic superscripts are significantly different

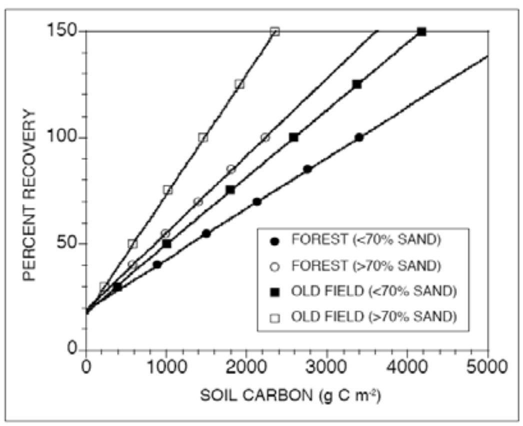

Figure 50. Levels of soil quality defined by soil carbon.

Table 17. Soil carbon and nitrogen in particulate organic matter (POM) and mineral associated organic matter (MOM), refractory soil carbon (determined by acid-base digestion), and corrected POM-C (adjusted for refractory soil carbon) in surface (0–20 cm) mineral soils from different disturbance categories at Fort Benning, GA.

Variable	Disturbance category				
	RF	LU	HU	MU	RM
POM-N (mg POM-N g^{-1} soil)	0.083^{a} (0.32)	0.072^{a} (0.54)	0.0^{b}	0.016^{b} (1.32)	0.009^{b} (0.75)
MOM-N (mg MOM-N g^{-1} soil)	0.21^{a} (0.10)	$0.20^{a,b}$ (0.45)	0.08^{c} (0.28)	0.27^{a} (0.21)	$0.15^{b,c}$ (0.04)
Uncorrected POM-C (mg POM-C g^{-1} soil)	4.25^{a} (0.34)	4.11^{a} (0.24)	0.35^{b} (0.54)	1.15^{b} (0.44)	1.51^{b} (0.21)
Refractory C (fraction)	0.36^{a} (0.19)	0.37^{a} (0.21)	0.67^{a} (0.57)	0.37^{a} (0.60)	0.33^{a} (0.14)
Corrected POM-C (mg POM-C g^{-1} soil)	2.67^{a} (0.24)	2.62^{a} (0.28)	0.16^{b} (1.21)	0.76^{b} (0.63)	1.02^{b} (0.28)
MOM-C (mg MOM-C g^{-1} soil)	5.35^{a} (0.27)	5.70^{a} (0.39)	1.42^{b} (0.32)	4.96^{a} (0.02)	$3.34^{a,b}$ (0.10)
Refractory C (mg C g^{-1} soil)	1.58^{a} (0.53)	1.49^{a} (0.32)	0.19^{b} (0.48)	0.39^{b} (0.40)	0.49^{b} (0.07)

Coefficients of variation are in parenthesis. Means in the same row with different alphabetic superscripts are significantly different. Sample size is 3 for each mean (except those under RM where $n = 2$). RF: reference site; LU: light military use; HU: heavy military use; MU: moderate military use; RM: remediated site.

Model to represent land cover type differences in the affects of disturbance on forest recovery and the dynamics of Soil C, N, and organic matter.

This is a compartment-based model of soil carbon and nitrogen dynamics that is capable of predicting forest recovery rates on degraded soils and forest sustainability, following recovery, under different regimes of prescribed fire and timber management. As part of model development, the effect of prescribed burning and forest thinning or clearcutting on stand recovery and sustainability was evaluated. The structural components of the model include; a) Tree biomass submodel that predicts aboveground and belowground tree biomass, b) Litter production submodel that includes the dynamics of herbaceous aboveground and belowground biomass, c) Soil C and N submodel that predicts total soil C and N stocks (to a 30 cm soil depth) as well as net soil N mineralization, and d) Excess N submodel that calculates the difference between predicted plant N demands and soil N supplies. A feedback loop reflecting the affect of potential excess nitrogen (PEN) on tree growth such that forest growth was limited under conditions of nitrogen deficiency. Consistent with experimental and observational findings, model predictions indicated that:

1. Forest recovery and sustainability are directly affected by how prescribed fire affected PEN. Similar to Collins' SEMP findings, prescribed fire impacted soil N supplies by lowering predicted soil C and N stocks which reduced the soil N pool that contributed to the predicted annual flux of net soil N mineralization.
2. Soils with inherently high N availability, increasing the fire frequency in combination with stand thinning or clearcutting had little effect on predictions of forest recovery and sustainability. However, combined effects of stand thinning (or clearcutting) and frequent prescribed burning could have adverse effects on forest recovery and sustainability when N availability was at the point of limiting forest growth.
3. For most areas, model predictions indicated that prescribed burning with a 3-year return interval would decrease soil C and N stocks, but would not adversely. However, the same fire return interval would affect sustainability of barren areas.
4. On soils with inherently low N availability, prescribed burning with a 2-year return interval depressed predicted soil carbon and nitrogen stocks to the point where soil nitrogen deficiencies prevented forest recovery as well as forest sustainability following recovery (Garten, 2004).

Table 18. Mean (±SE) soil carbon and nitrogen stocks as a function of soil depth under different land cover categories at Fort Benning, GA.

Soil depth (cm)	Soil carbon stock (g C m⁻²)			Soil nitrogen stock (g N m⁻²)		
	Barren	Transitional land	Forest	Barren	Transitional land	Forest
0-10	292 ±106	1616 ±188	1658 ±126	21.1 ±4.6	86.8 ±16.1	81.7 ±8.2
10-20	238 ±92	963 ±103	767 ±61	19.3 ±5.2	49.3 ±7.4	40.4 ±4.2
20-30	185 ±68	528 ±61	560 ±61	14.8 ±4.3	38.2 ±7.3	35.3 ±4.0
30-40	148 ±60	364 ±30	425 ±49	14.4 ±3.9	32.1 ±5.1	31.2 ±2.9

Table 19. Effect of harvesting (0, 50, or 99% removal of AGWB) and frequency of prescribed burning (FIREFREQ) on predicted recovery of aboveground forest biomass (AGWB, g m^{-2}), soil C stocks (SOC, g C m^{-2}) on soil with low and high N availability (experiment 1). The time interval between thinning (50% removal) or clearcutting (99% removal) was 50 years. The predicted values were summarized following a 100-year modle run.

REMOVAL %	FIREFREQ (years)	Low soil N availability				High soil N availability			
		AGWB	SOC	SOILN	PEN	AGWB	SOC	SOILN	PEN
0	No fire	17913	5210	248	1.91	17931	5221	149	5.00
	3	16861	3334	159	-0.19	17931	3527	101	1.90
	2	5439	2141	102	-0.04	17927	3336	95	1.56
50	No fire	17414	4982	237	1.76	17420	4987	142	4.71
	3	16125	3218	153	-0.19	17420	3390	97	1.79
	2	4769	2117	101	-0.00	17418	3213	92	1.47
99	No fire	16921	4755	226	1.61	16921	4757	136	4.42
	3	15183	3089	147	-0.19	16921	3256	93	1.68
	2	5258	2113	101	-0.04	16921	3093	88	1.38

Table 20. Mean (±SE) concentrations (µg N g^{-1} soil) of extractable (2 M KCL) ammonium- and nitrate-N from surface (0–20 cm) mineral soil samples under different land cover categories at Fort Benning, GA.

Form of nitrogen	Land cover category					F-value
	Barren	Transitional land	Evergreen forest	Mixed forest	Deciduous forest	
NO_3-N	0.68^{a} ±0.23	0.38^{ab} ±0.07	0.13^{b} ±0.03	0.18^{b} ±0.04	0.13^{b} ±0.03	4.7 ($P < 0.01$)
NH_4-N	0.37^{a} ±0.16	1.48^{ab} ±0.36	1.32^{ab} ±0.22	2.41^{b} ±0.74	2.12^{b} ±0.60	2.8 ($P < 0.05$)
Inorganic N	1.05^{a} ±0.32	1.85^{a} ±0.35	1.45^{a} ±0.23	2.58^{a} ±0.77	2.26^{a} ±0.61	1.6

* Means in the same row with different alphabetic superscripts are significantly different

Landscape Model for Spatial Patterns of Soil C and N and Potential Non-Point N Sources

This is a GIS based predictive model to assess non-point landscape sources of N and C. Analysis was performed in the following steps: (1) development of a conceptual model to quantify potential excess soil nitrogen (PEN), (2) acquisition and re-categorization of a land use/cover map of Fort Benning that was derived from Landsat Thematic Mapper data, (3) development of nitrogen flux maps for each of five nitrogen cycle processes by acquisition of field data and estimation of nitrogen fluxes under different land covers from a literature review, (4) calculation of seasonal and annual PEN using GIS-based spatial models, and (5) comparison of PEN between land use categories. Information and experience obtained as a result of this technical objective will contribute to another SERDP Project (SERDP 1259) directed at developing a regional simulation model (RSim) to explore impacts of resource use and constraints in the five county region surrounding Fort Benning. The most significant findings to date include:

1. The model predicted the spatial distribution of seasonal and annual nitrogen sources and sinks and estimated the amount of nitrogen flux using a mass balance model of three input processes (atmospheric nitrogen deposition, fertilization, net soil nitrogen mineralization) and two output processes (plant uptake and denitrification).

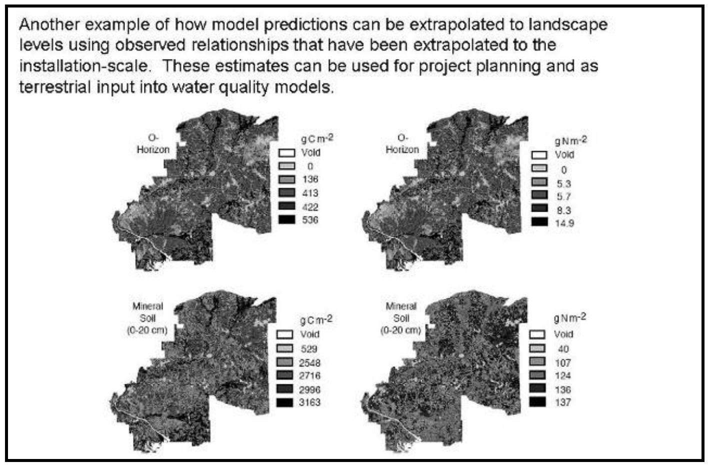

Figure 51. Hypothesized spatial distributions of soil carbon and nitrogen stocks at Fort Benning based on the assignment of field measurements to an installation land cover map from 1999.

2. Net soil nitrogen mineralization was the primary contributing process to annual and seasonal estimates of PEN. Potential excess nitrogen was positive (a potential source) when potential inputs exceeded potential outputs. Negative PEN indicated a potential sink.
3. The results indicated that most of Fort Benning is a net sink for nitrogen only 6 % of the landscape was identified as a source of PEN. Positive PEN values were primarily associated with urban land uses, particularly roads and cantonment areas. Barren areas were also identified by the model as having positive PEN values.

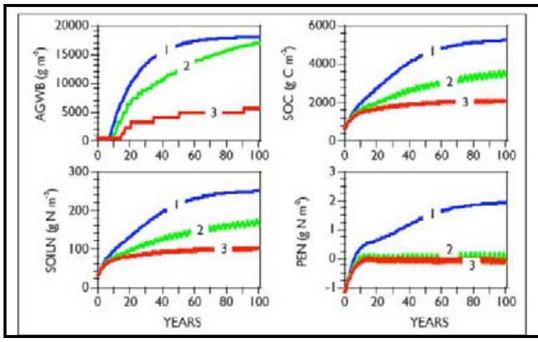

Figure 52. Effect of prescribed burning on aboveground tree biomass (AGWB), soil C Stock (SOC), soin N stocks (SOILN), and potential excess N (PEN) on less sandy soils. Legend: (1) blue line = no fire; (2) green line = prescribed burn once every 3 yrs; (3) red line = prescribed burn once every 2 yrs.

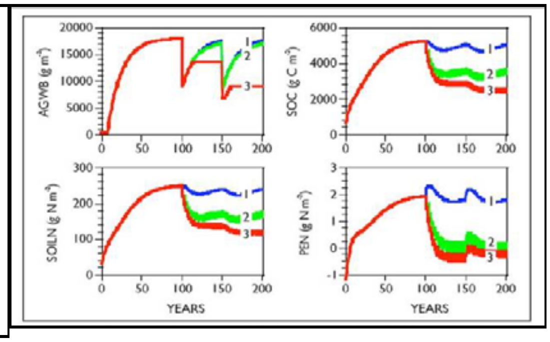

Figure 53. Effect of prescribed burning and timber management (50% forest thinning at 100 and 150 yrs), following forest recovery, on aboveground tree biomass (AGWB), soil C Stock (SOC), soin N stocks (SOILN), and potential excess N (PEN) on less sandy soils. Legend: (1) blue line = no fire; (2) green line = prescribed burn once every 3 yrs; (3) red line = prescribed burn once every 2 yrs.

Journal articles

Garten, C.T., Jr., T.L. Ashwood, and V.H. Dale. 2003. Effect of military training on indicators of soil quality at Fort Benning, Georgia. Ecological Indicators 3:171-179.

Garten, C.T., Jr., and T.L. Ashwood. 2005. Modelling soil quality thresholds to ecosystem recovery at Fort Benning, Georgia. Ecological Engineering. 23:351-369

Garten, Jr., C.T. 2006. Predicted effects of prescribed burning and harvesting on forest recovery and sustainability in southwest Georgia. Journal of Environmental Management 81: 323-332.

Maloney, K.O, C.T. Garten, Jr., and T.L. Ashwood. 2008. Changes in soil properties following 55 years of secondary forest succession at Fort Benning, Georgia, USA. Restoration Ecology 16 (3): 503-510..

Technical reports

Garten, C.T., Jr., and T.L. Ashwood. 2004a. Land cover differences in soil carbon and nitrogen at Fort Benning, Georgia. ORNL/TM-2004/14. Oak Ridge National Laboratory, Oak Ridge, TN.

Garten, C.T., Jr., and T.L. Ashwood. 2004b. Modeling soil quality thresholds to ecosystem recovery at Fort Benning, Georgia, USA (ORNL/TM-2004/41). Oak Ridge National Laboratory, Oak Ridge, TN.

Garten, C.T., Jr. 2004. Predicted effects of prescribed burning and timber management on forest recovery and sustainability at Fort Benning, Georgia (ORNL/TM-2004/77). Oak Ridge National Laboratory, Oak Ridge, TN.

Garten, C.T., Jr., and T.L. Ashwood. 2004c. Effects of heavy, tracked-vehicle disturbance on forest soil properties at Fort Benning, Georgia (ORNL/TM-2004/76). Oak Ridge National Laboratory, Oak Ridge, TN.

Garten, C.T., Jr. 2004. Disturbance of soil organic matter and nitrogen dynamics: implications for soil and water quality. Project Final Report. Oak Ridge National Laboratory, Oak Ridge, TN.

SEMP Project CS-1114E-00: Thresholds of Disturbance: Land management effects on vegetation and nitrogen dynamics (PI: B. Collins, Savannah River Ecology Laboratory)

Baseline surveys conducted in 2000 and 2001 revealed that military training and frequent fire have, over the longer term (decades), interacted with soil texture to influence forest canopy and ground layer composition, and soil conditions, at Fort Benning.

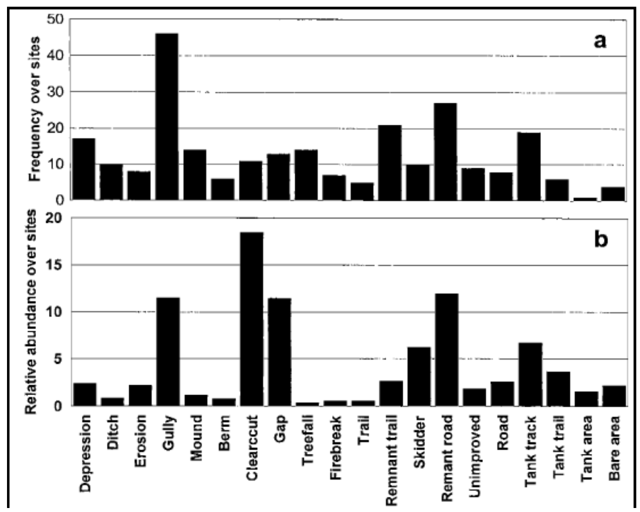

Figure 54. (a) Frequency (number encountered over all sites) and (b) relative abundance (length of transect of feature/total length of sample line over all sites) of natural and land-use disturbance features in 32 400X400-m sites.

Field surveys of disturbance features revealed that land use or natural disturbance features occupied from 7% to 50% of the area sampled in each site. Road-like features, including active and remnant trails, roads, and vehicle tracks or trails, were, collectively, the most frequent and abundant disturbance (Figure 54). Interestingly, these disturbance types are likely to overlay historical legacy disturbances associated with post-settlement agriculture. Disturbance features were most abundant on clayey sites (MhC) in heavy military use areas (Figure 54). Potentially, the greater frequency of disturbance features on the clayey sites may simply reflect differences in surface soil recovery rate. Patterns of variation were similar between soil types and training intensities. Overall, the line-transect method proved effective in define local scale disturbance "artifacts" that may continue to influence ecosystem processes and development as well as be a collectively useful tool to characterize past disturbance intensities.

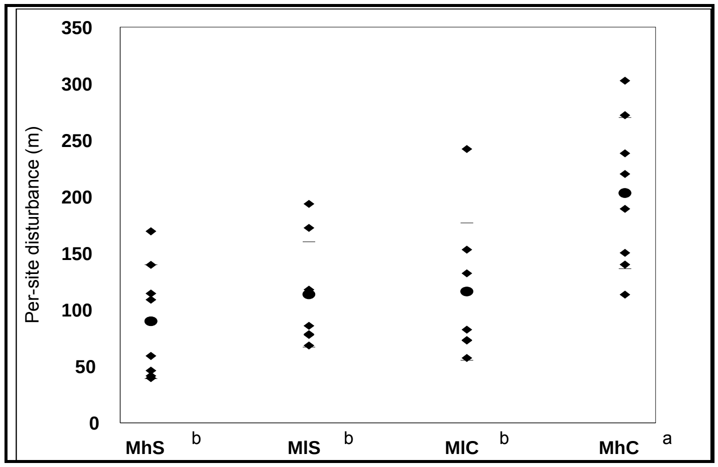

Figure 55. Mean (circle) and standard deviation (lines) of disturbance features in which each military training/soil texture category. Also shown are the means for each site within the catgory (diamonds).

Consistent with other SEMP studies, the 32 upland forest stands selected for treatment comparisons had differences in soil properties related to soil texture and military land use intensity (Table 21). Results suggest organic layers in sandy compared to clayey sites could immobilize nitrogen through relatively slow rates of decomposition and nitrogen release to the mineral soil, but mineralization processes in the mineral soil could enhance nitrogen availability, especially in land compartments with heavier military training. In clayey sites, greater organic layer mass, particularly in sites with lighter military use, favors faster decomposition, but the lower nitrogen availability observed in the field on the heavier use sites suggests mineralized nitrogen can be bound by fine soil particles.

Table 21. Soil properties related to soil texture and military land use intensity.

Variable	Clayey soil		Sandy soil	
	Light use	Heavy use	Light use	Heavy use
Bulk density (g cm^{-3})	1.17 (0.03)	1.25 (0.03)	1.27 (0.04)	1.40 (0.03)
C concentration (%)	2.03 (0.17)	1.32 (0.19)	1.16(0.10)	0.92 (0.10)
C stock (g C m^{-2})	3539.27 (301.00)	2428.13 (348.01)	2139.63 (171.15)	1899.11 (205.40)
N concentration (%)	0.081 (0.007)	0.042 (0.003)	0.036(0.003)	0.031 (0.002)
N stock (g N m^{-2})	141.28 (12.96)	77.34 (4.75)	65.35(5.40)	64.91 (3.24)
C:N ratio	26.37 (1.29)	29.22 (1.91)	34.42 (1.70)	28.88 (2.33)

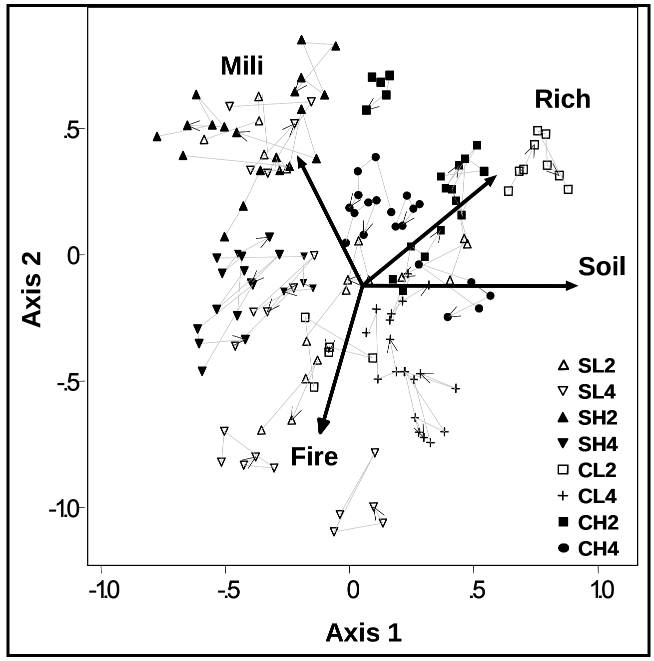

Figure 56. Results derived frm using Multivariate techniques to compare sites.

Using Multivariate techniques to compare sites, ordination revealed a strong effect of military training on initial (2000, 2001) canopy and ground layer composition. The canopy tree ordination also reflected the proportion of pine, particularly longleaf pine. Four canopy types were distinguished, all based on the dominant canopy trees: longleaf pine, shortleaf pine, mixed pine-hardwood, and loblolly pine stands. Although differences were less pronounced than in the canopy, ground layer vegetation also reflected the canopy dominant. Pine-hardwood and longleaf stands had different ground layer composition. *Andropogon* sp., primarily broomsedge, *A. virginicus*, *Pityopsis spp.*, and sweetgum (*Liquidambar styraciflua*) seedlings were abundant in multiple canopy types. Pine-hardwood forests had abundant *Vitis* sp, while bracken fern (*Pteridium aquilinum*) was abundant in longleaf stands. As expected, the abundance of legumes and grasses was higher in the longleaf stands than in the other forest types. For all forests types, 70 % pine canopy appears to be a threshold for ground layer vegetation with abundant grasses and legumes. Interestingly, other investigators elsewhere have suggested a similar threshold for savanna-like understories in longleaf pine systems (Outcult 1999, Boyer 1996, Allard and Peet 1991, Walker 2000) as well as shortleaf pine systems (Guldin et al.1999). Overall, the observed vegetation patterns are consistent with the findings for the maturing forest systems studied by other SEMP groups as well as studies elsewhere in the sandhill physiographic province (Peet 2005).

Table 22. Mean (SE) abundance (mean detections/point/land use category) of selected avian species in recently burned heavy use (1H) and light use (1L) and 3rd growing season post-fire heavy use (3H) and light use (3L) land use categories at Fort Benning, GA, May 2002.

	Land Use Category			
	1H	1L	3H	3L
Early successional or pine-grassland species				
Bachman's Sparrow (*Aimophila aestivalis*)	0.50 (0.15)	0.50 (0.19)	0.33 (0.14)	0.35 (0.20)
Brown-headed Cowbird (*Molothrus ater*)	0.20 (0.12	0	0	0.15 (0.08)
Eastern Towhee (*Pipilo erythrophthalmus*)	0.50 (0.14)	0.45 (0.14)	0.61 (0.16)	0.55 (0.14)
Indigo Bunting (*Paserina cyanea*)	1.50^{a} (0.27)	0.95^{ab} (0.21)	1.11^{ab} (0.24)	0.65^{b} (0.18)
Northern Bobwhite (*Colinus virginianus*)	0.35^{a} (0.35)	0.85^{ab} (0.25)	0.78^{ab} (0.21)	0.25^{b} (0.10)
Prairie Warbler (*Dendroica discolor*)	1.05 (0.29)	0.95 (0.23)	0.94 (0.21)	1.10 (0.22)
Yellow-breasted Chat (*Icteria virens*)	0.25 (0.12)	0.50 (0.15)	0.33 (0.14)	0.60 (0.13)
Species combined*	5.15 (0.50)	4.20 (0.75)	4.11 (0.62)	3.50 (0.52)
Forest species or habitat generalists				
Carolina Wren (*Thryothorus ludovicianus*)	0.70^{ab} (0.16)	0.80^{ab} (0.19)	0.44^{b} (0.12)	1.25^{a} (0.20)
Great-crested Flycatcher (*Myiarchus crinitus*)	0.65 (0.13)	0.55 (0.11	0.78 (0.15)	0.55 (0.14)
Northern Cardinal (*Cardinalis cardinalis*)	1.30 (0.28)	0.80 (0.20)	1.33 (0.21)	1.15 (0.23)
Pine Warbler (*Dendroica pinus*)	0.75 (0.23)	0.75 (0.18)	0.78 (0.19)	0.65 (0.15)
Red-eyed Vireo (*Vireo olivaceus*)	0.35^{b} (0.13)	0.45^{ab} (0.15)	0.33^{b} (0.11)	0.90^{a} (0.18)
Summer Tanager (*Piranga rubra*)	0.55 (0.14)	0.35 (0.11)	0.44 (0.12)	0.45 (0.11)
Tufted Titmouse (*Baeolophus bicolor*)	0.45 (0.15)	0.35 (0.11)	0.83 (0.15)	0.80 (0.20)
Species combined	4.75^{ab} (0.44)	4.05^{b} (0.48)	4.94^{ab} (0.37)	5.75^{a} (0.39)

Abundance means with the same letter and without a letter do not differ significantly ($P > 0.10$).
*Does not include brown-headed cowbird abundance.

Comparison between the study treatments and their indirect impacts on ecosystem characteristics and features reveal that training and soil conditions indirectly influence bird communities through their impact on vegetation, particularly understory features. Essentially, independent of training-use and burning, sandy soils were less dominated by grasses when compared with those with more clay. Mid-story cover and density was reduced by both training and burning. Mid-story and canopy composition reflect texture as well as the combined influences of training and burning. Heavy training reduces the number and density of bird species associated with forested conditions. Some individual species were more responsive to just training (e.g., northern bobwhite, yellow chat), others more responsive to post-burn conditions (tufted titmouse, bachman's sparrow), and still others having more complex relationships (red-eyed vireo, Carolina wren). These differences in response are likely to reflect species-specific habitat requirements. These findings are likely to be representative of other guild relationships to disturbance that have been identified elsewhere and include herptofauna, small mammals, and bats.

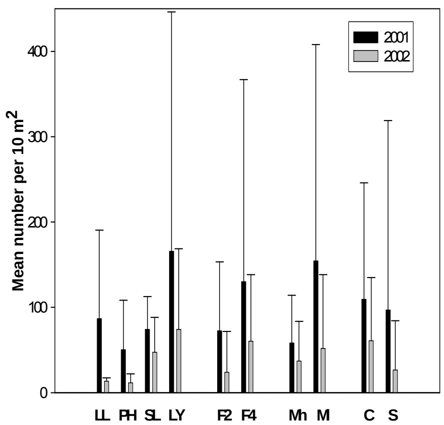

Figure 57. Mean density of pine (P. palustris, P. taeda, P. sp.) seedlings in forest types (Longleaf (LL), Pine-hardwood (PH), Short-leaf (SL), Loblolly (LY)), 2-yr (F2) and 4-yr (F4) fire catego-ries, heavier (Mh) and lighter (Ml) military use sites, and sandy (S) and clayey (C) soil sites.

Thirty-two locations were used to experimentally evaluate the interaction between soil texture (s=sand, c=clay), military training (l=light, h=moderate), and burn interval (2 yr., 4 yr.). Vegetation analyses reveal that shorter, 2-yr fire interval caused the ground layer vegetation to become more similar to that of clayey sites with heavier military use; i.e., to be characterized by xeric sandhills species and other non-woody legumes, graminoids, and forbs. This finding was unexpected, xeric sandhill species were expected to be associated with heavily disturbed sandy soils. This suggests that ecosystem stress likely defines the influence of soil features on plant communities, and the effects mimicked through heavy disturbance. These analyses involved the development of a new Non-metric Multi-Dimentional Scaling (NMDS) method that focused on weighted vector analysis of compositional change within multi-dimentional space (Figure 57). Overall, vector length and direction during the repeated sampling period was not consistent within or between treatment groups. Thus, suggesting that because of differences in initial vegetation conditions, and independent of land-use, a limited number of burning events is not sufficient to redirect compositional patterns toward a convergent condition. As a technique NMDS can be an effective predictive tool once DFC conditions have been characterized within multivariate space, ordination techniques in combination with vector analysis of repeated samples can be used to document progress toward DFC conditions.

Consistent with Garten's SEMP findings, prescribed burning at Ft Benning reduces the soil organic layer which is a largely immobilizing nitrogen pool in these systems (Figure 58). The removal doesn't represent a reduction in immediate nitrogen availability, but rather a reduction in total N pool. Therefore, too frequent burning or combined disturbance results in the capacitance to store nitrogen. The longer-term consequences of this removal are not well understood and a long-term monitoring plan should address this to ensure the system doesn't trend toward nitrogen deficiency. In healthy systems, N limitation through repeated burning representative of natural cycles is a regulating condition and necessary for proper function and does not lead to N deficiency (Hendricks et al. 1998, Boring et al. 2004). Presently, on most sites, N fixation does not supply sufficient fixed nitrogen to offset these organic layer nitrogen losses. Similar findings have been reported to occur in stressed ecosystems elsewhere in the Sandhill and upper Coastal Plain regions, but contrast most studies of the lower Coastal Plain were leguminous N-fixation is sufficient to counterbalance combustive N losses. These findings may suggest a dichotomy in function and process either between the Outer Coastal Plain and Sandhill

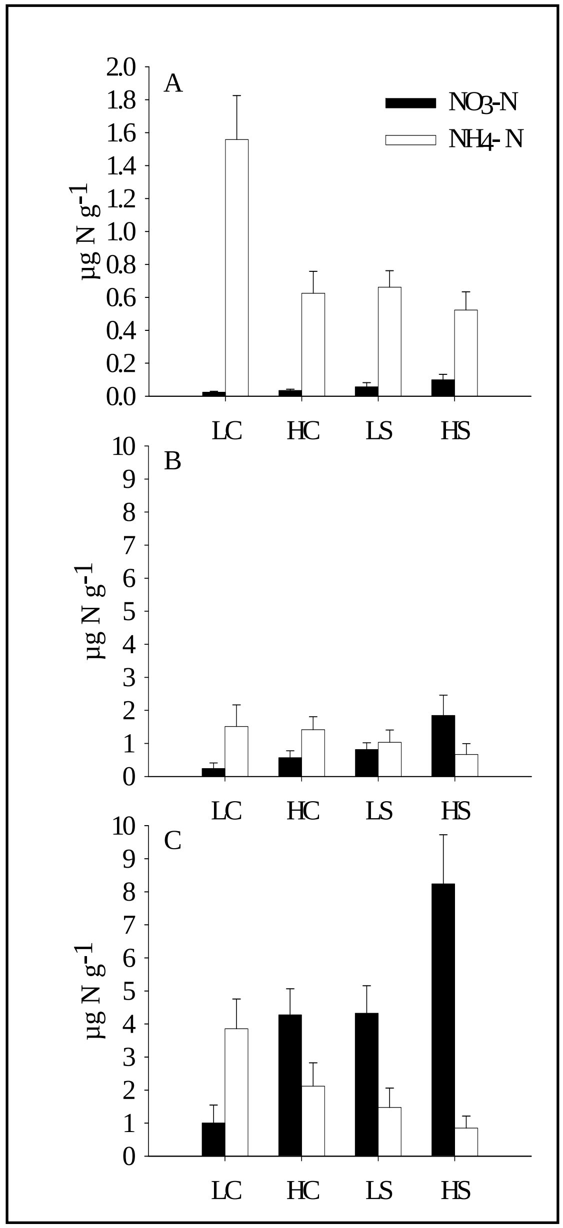

Figure 58. Mean (+ std. error) extractable soil NO3-N and NH4-N, (A) initial extraction, (B) after aerbic 42-day incubation, (C) cumulative production after aerobic 84-day incubation. LC=lighter use/clayey soil, LS=light use /sandy soil.

regions or between intact longleaf pine and post-agriculture, successional mixed pine systems.

Comparisons between longleaf and initially dissimilar sites revealed either: (1) heavier military use or shorter fire frequency in clayey sites, or (2) shorter fire frequency in sandy sites can maintain ground layer composition similar to that of longleaf sites. These results partially support our hypothesis that the magnitude of ecosystem response to fire and military training disturbance would be less, and the transition to pine-dominated forest faster, for sites on sandy soils; shorter fire frequency alone can maintain longleaf ground layer composition on sandy sites, but both shorter fire frequency and heavier military training may be needed in clayey sites.

Comparisons between longleaf and initially dissimilar sites revealed the shorter, 2-yr fire interval was not sufficient to shift ground layer composition to the longleaf domain. Shorter fire interval did not cause sites that were initially different to become more like, or initially similar sites to diverge from, longleaf communities. This study did not address the cumulative effects of multiple fire events but does illustrate that a 1-2 burn events does not result in conversion toward longer term goals.

Overall, within the context of Fort Benning ecosystem management model and SREL's research design, the longer, 4-yr fire intervals in sandy sites or the combination of longer fire interval and lighter military use in clayey sites may cause sites to move away from the longleaf domain and lengthen the successional trajectory. In contrast, a 2-yr fire interval and heavier military use in clayey sites or the 2-yr fire interval in sandy sites may maintain sites within the desired longleaf understory domain. However, in sampled stands the more frequent burning did not result in high levels of legume abundance and associated N inputs, which could offset nitrogen losses due to fire.

An interesting finding in these training-stressed systems was that more frequent burning did not promote longleaf regeneration sufficient to hasten transition to a longleaf pine forest. Thus, despite promoting desirable understory composition, more frequent fire may inhibit regeneration. These results only partially support out hypothesis that the more open environment generated by heavier training and frequent fire could promote regeneration of species typical of pine ecosystems, and hasten transition to a longleaf pine forest. If seedling establishment limitation is overcome, e.g., by planting, management that maintains a relatively open canopy (prescribed fire, thinning) and low soil disturbance (lighter compared to heavier military training), can promote growth into grass, rocket, and sapling stages. In summer, 2004, after all sites were burned following both 2-yr fire intervals and one 4-yr fire interval, the number of grass stage individuals in a stand increased with the number of historical fires (1980-2000), longer time since fire, and the percent of sand in the soil; the number of rocket stage individuals increased with increasing number of historical fires. These conditions were common in longleaf and shortleaf stands that had experienced higher fire frequency and forest management for an open canopy, but lighter military use.

We conclude that management to restore longleaf pine forests must overcome recruitment limitations and, on severely disturbed sites, may be inhibited by frequent fire. In addition, restoration of a more legume-dense groundcover would aid in nitrogen supply to these forests (Hendricks et al. 1998). Unfortunately, the unaided establishment of legumes, particularly heavy-seeded perennials, may be impacted by intermediate-levels of military training (Dale 2006), limited by legacy land-use (Smith 1999, Smith and Walker 2001, Frost 1996), or dispersal-impacted by habitat fragmentation (Gonzales & Hamrick 2005). If longleaf pine recruitment limitation is overcome, management that maintains a relatively open canopy and low soil disturbance can promote growth into grass, rocket, and sapling stages and may facilitate restoration of longleaf pine ecosystem as conceptualized in the Fort Benning ecological restoration model.

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Technical report (submitted)

Collins, B. Thresholds of Disturbance: Land Management Effects on Vegetation and Nitrogen Dynamics Project Final Report. Savannah River Ecology Laboratory. (Submitted April 2005)

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Drake, S. J. 2004. Groundcover carbon and nitrogen cycling and legume nitrogen inputs in a frequently burned mixed pine forest. M. S. Thesis, University of Georgia.

An overview of the SEMP integration project

Synthesis of research results and integration of ecological indicators

Dale (2006) developed a framework for integrating and analyzing the data collected at Fort Benning by many researchers across the five teams. Using retrospective analysis, indicators that discriminated land-management categories were identified. There were two key components to this work, (1) the development of land-management categories and (2) variable screening by multiple solutions.

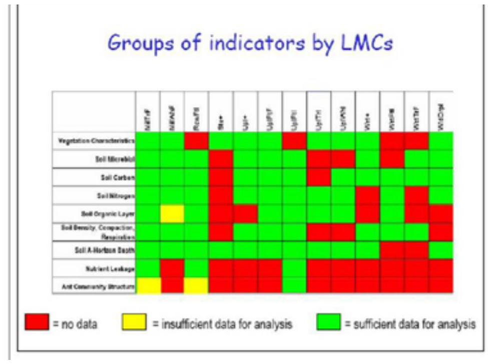


Figure 59. SEMP project integration.

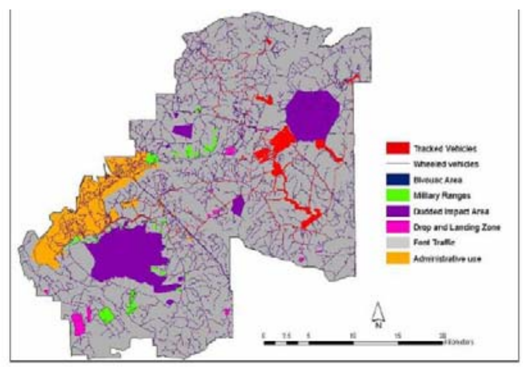


Figure 60. Military use of land.

The land-management category (LMC) matrix provides a means of identifying discrete areas at Fort Benning that have a unique land-management goal, military training type and intensity, as well as activity frequency. Criteria for indicator selection were finalized through discussions with the research teams and with Fort Benning resource managers. Evaluation criteria were divided into two groups: those based on technical effectiveness and practical utility.

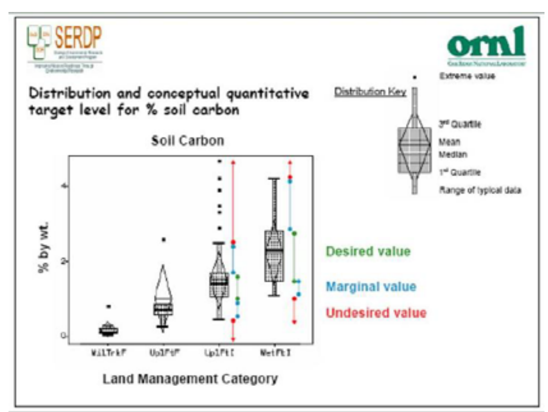
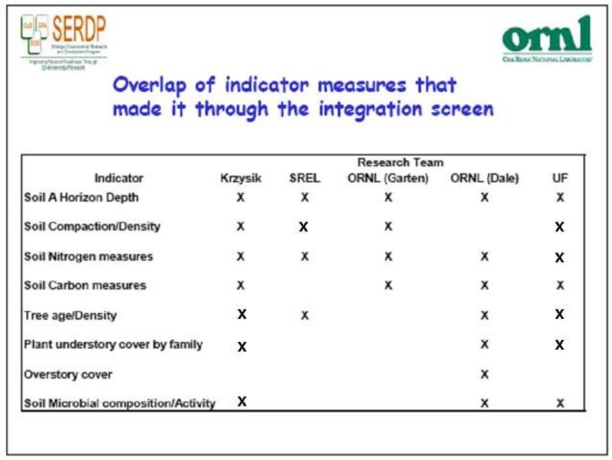


Figure 61. Distribution .and conceptual quantitative target level for % soil carbon.

Data from the individual indicator projects were collected from the research teams, and statistical analysis is complete. Based on analysis, a list of the indicators suitable for site, watershed, and landscape scale of assessment was developed. Conceptual models were developed that show how the indicators vary across time and space. These models also reflect great variation in the indicators across the biological hierarchy.

Principal findings

A collective vision for the land can be derived among resource managers with diverse objectives if care is taken to be sure that terms are communicated clearly and if all stakeholders have the opportunity to participate in discussions.



Indicator	Krzysik	SREL	ORNL (Garten)	ORNL (Dale)	UF
Soil A Horizon Depth	x	x	x	x	x
Soil Compaction/Density	x	x	x		x
Soil Nitrogen measures	x	x	x	x	x
Soil Carbon measures	x		x	x	x
Tree age/Density	x	x		x	x
Plant understory cover by family	x			x	x
Overstory cover				x	
Soil Microbial composition/Activity	x			x	x

Figure 62. Overlap of indicator measures that made it through the integration screen.

Land-management categories can be developed based on management goal for each area, the use of the land, and the frequency of that use. These land management categories provide a meaningful way to resource managers to formalize their goals for the land given expected uses and to identify indicators that can be used to monitor if each goal is on track.

Multivariate analysis supports our hypothesis that ecological indicators should come from a suite of spatial and temporal scales and environmental assets. Following analysis of all parameters considered by the SEMP and other relevant studies, a list of recommended indicators was developed. Do to a difference in availability and accessibility some data and techniques received more comprehensive review:

1. Key indicators at the plot levels include:
   a. Soil physical and chemical variables: soil “A” horizon depth, compaction, organic matter, organic layer N, Total N, N mineralization rate, Total Carbon and % Carbon.
   b. Soil microbiological indicators: biomarkers for fungi, Gram-negative Eubacteria, soil microbial respiration and beta-glucosidase activity.
   c. Plant family and life form indicators: the Family Leguminosae, possibly Rosaceae, and the plant life forms such as Therophyte, Cyptophyte, Hemicryptophyte and Chamaephyte as well as understory cover, overstory cover and tree stand characteristics.

2. Key indicators at the watershed level are:
    a. Disturbance intensity
        (1) % bare area on slopes> 3%
        (2) % road coverage
    b. Dissolved organic carbon and pH
    c. Stream physical habitat
        (1) Coarse woody debris (CWD), BPOM
        (2) Bed sediment stability
    d. Macroinvertebrates
        (1) EPT (Ephemeroptera, Plecoptera, Tricoptera)
        (2) Chironomidae richness and GASCI
    e. Fish
        (1) Assemblage metrics
        (2) Population metrics
3. Key indicators at the landscape level are:
    a. Percent cover of cover types
    b. Total edge (with border) of patches
    c. Number of patches
    d. Mean patch area
    e. Patch area range
    f. Coefficient of variation within & between patches
    g. Perimeter to area ratio of patches
    h. Euclidean nearest neighbor patch distance
    i. Clumped distribution of patches

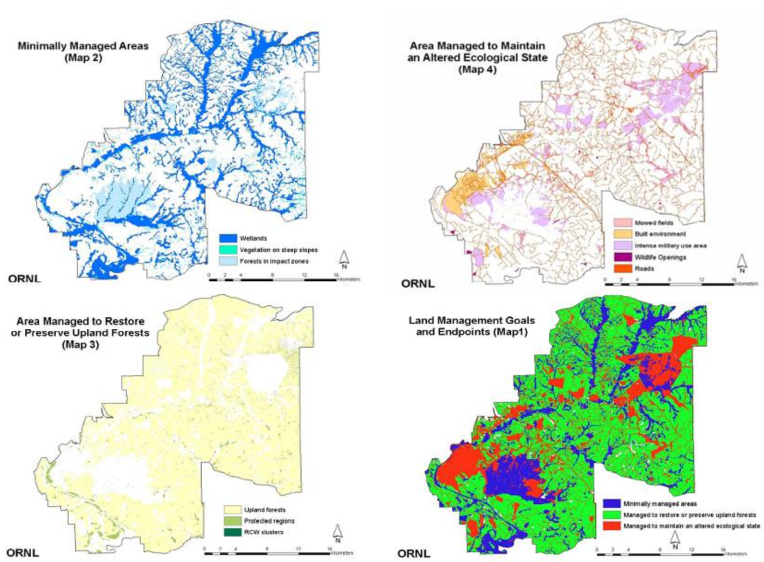


Figure 63. General use patterns and land management targets can be spatially expressed and used to develop strategies that avoid (user-group" conflict.

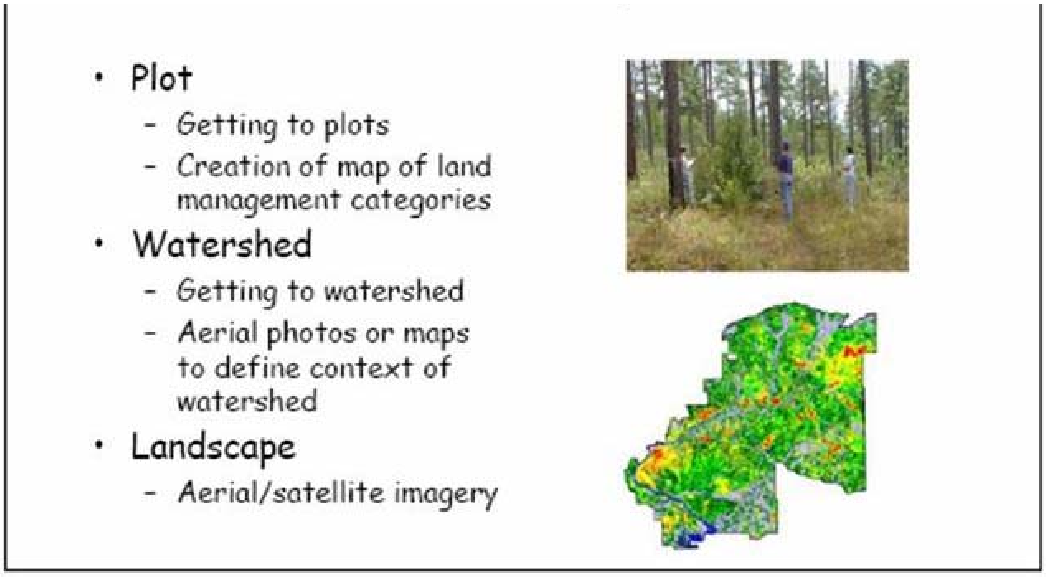


Figure 64. Return to criteria to select final indicators recognizing that base cost of obtaining indicators differs by scale..

Benefits

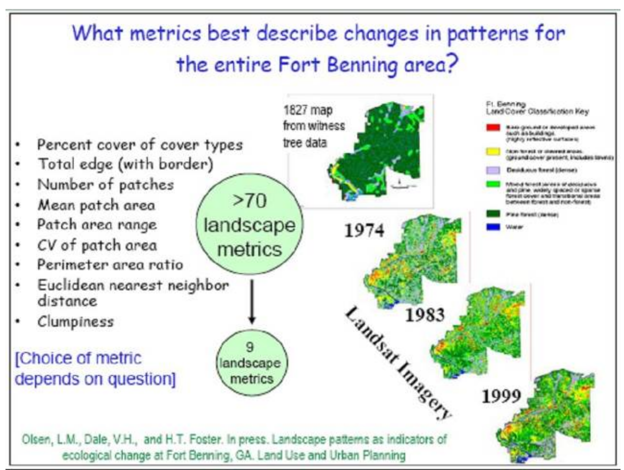


Figure 65. Metrics that best describe changes in patterns for the entire Fort Benning area.

The project identified a suite of indicators that Fort Benning resource managers can use to make judgments about the ecological condition of the installation. Specifically, the resource managers have noted that indicators will be useful for planning budgets, potentially providing advanced detection regarding compliance with environmental legislation, signaling whether the installation is on the right path toward achieving longer term goals, signaling whether the installation is on the right path to achieve shorter term objectives, and suggest need for targeted projects and research. The approach of developing and mapping land-management categories should be useful for other locations. It provides a means for communication across the various uses of the land, a format for collecting and interpreting monitoring data, and a framework for designing and implementing management goal. The specific indicators identified at Fort Benning are likely to be of great importance for other military installations in the southeast. The categories of important indicators are likely to important in all locations. The approach for analysis of indicators should be generally transferable. Collectively, all SEMP groups found better solution relationships involving multiple indicators as opposed to using a single variable.

Conclusions of SEMP integration project

The SEMP Integration project examined indicators for ecological changes at three levels of spatial resolution: the plot level, catchment or watershed, and landscape level. For the plots level study, a framework was developed that integrates data collected at Fort Benning by many researchers across the five teams. This approach first defined and mapped land-management categories and then considered if the plot-level indicators can separate between those categories. The retrospective analysis of the data collected by many research teams required a weight-of-evidence approach for the selection of indicators that best discriminated land-management categories. Although the data for this effort were not collected in a fashion commensurate with traditional statistical techniques, it was still possible to integrate the separate research efforts and score the results. The use of selection scores provided a straightforward comparison of each indicator and this was important in obtaining results

There were several major findings about how land management from this analysis. A collective vision for the land can be derived among resource managers with diverse objectives if care is taken to be sure that terms are communicated clearly and if all stakeholders have the opportunity to participate in discussions. Land-management categories can be developed based on management goal for each area, the use of the land, and the frequency of that use. These land management categories provide a meaningful way to resource managers to formalize their goals for the land given expected uses and to identify indicators that can be used to monitor if each goal is on track. Multivariate analysis supports the hypothesis that ecological indicators should come from a suite of spatial and temporal scales and environmental assets.

According to Dale, Krzysik's findings are consistent with aspects of the intermediate disturbance hypothesis (Grime 1984, Brown 1986, and others); whereby light disturbance thresholds results in the loss of some aspects of diversity and result in less efficient ecosystems, while exceeding heavy disturbance thresholds results in shift from dominance of ecosystem processes from those regulated by functional biological processes to those governed by physical laws. Taken to an extreme, there is a shift from secondary successional processes toward primary succession processes and a significant shift in time towards recovery.

Examining a suite of landscape metrics over time was useful for summarizing, describing, and assessing land-cover change at Fort Benning. The FRAGSTATS and ATtILA programs were relatively simple to use and provided information pertinent to understanding and managing the land. Therefore, we encourage resource managers to use landscape metrics to analyze changes in patterns of land cover over time examine how human activities have affected an area.

Several investigators and analysts have suggested that broad-scale monitoring criteria at multiple ecosystem levels are needed to monitor trends in biodiversity and functional efficiency (Noss et al. 1995). Such a system does exist for some ecological systems (e.g., IBI stream criteria), and has been iteratively improved by region (Mulholland 2004). Since development, several investigators have proposed modifications as to use of disturbance "sensitive" guilds to evaluate the state and condition of landscapes and streams.

Data collected for disparate purposes can be used to help develop an understanding of land-cover changes over time and are often necessary to further our knowledge of historic conditions on a given landscape. For the entire Fort Benning landscape, the values of landscape metrics for 1827 were very different from the values for recent decades. While the changes between 1827 and 1974 may be somewhat exaggerated due to data constraints, we can conclude that the nineteenth century landscape at Fort Benning was composed largely of uninterrupted pine forest with some deciduous forests found in riparian corridors and some open areas associated with Native American settlements. Land cover and land use in the 1 970s were considerably different. Following decades of farming, military training activities had a pronounced effect upon the landscape. Heavy training activities resulted in areas of sparse land cover and bare ground. Interestingly, these areas have largely persisted on the landscape throughout the 1980s and 1990s. This result not only emphasizes the lasting footprint that military activities have on the landscape but also highlights the efforts made by management to confine heavy training exercises to certain sacrifice areas. Another interesting trend occurred in the 1990s. Pine forests have been on the rise as is reflected in both landscape composition and patch dynamics such as largest patch size, number of patches, and total edge. Management efforts at Fort Benning have focused upon managing for longleaf pine. These efforts appear to be decreasing hardwood invasion in favor of pine species in many areas on the installation.

Journal articles

Published

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Wolfe, A.K. and V.H. Dale. Using a delphi approach to define land-management categories and to integrate science and practice. Environmental Management. (In revision March 2005)

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5 Consensus Findings and Synthesis of Collective Observations

The concept of “indicators” is dependent on objectives and purpose. Sustainability to meet compliance objectives require tighter definition of conditions; hence processes that sustain or support those conditions. In contrast, Sustainability to meet training objectives may simply be the maintenance of ecological or training settings that can capable of successful revegetation or reestablishment. For the most part, the initial SEMP projects focused on “ecological sustainability” and associated indicators as being those features that would allow for natural sustainment without investment and constainted land-use objectives. As an example, most SEMP studies did not consider indicators that would aid in the assessment of processes associated with ITAM mitigation and remediation success, nor progress toward well-defined RCW habitat criteria that leads to species recovery. Inference from both examples, suggests only partial overlap of sustainable soil-associated conditions are needed; therefore only partial overlap of indicators. The SEMP studies considered indicating factors that could be used to evaluate continued advancement and maintenance of current and succeeding conditions with broad application of existing or passive management and land-use patterns. Therefore, the initial SEMP studies have limited application toward decision-making because land-use decisions are reliant on specific conditional criteria that have insitu concepts of successful maintenance and sustainability; but, the SEMP studies do provide useful information for multiscalar modeling assessments and trend analysis, as well as insight toward the development of broadened monitoring programs.

Most DOD lands are dedicated to military training and support; thus, the first priority is to meet current and projected needs to support and training. These needs include range development and maintenance, infrastructrure networks, and range rehabilitation and mitigation. However, training is also dependent upon meeting stewardship and compliance obligations (e.g., NEPA, Endangered Species Act, Clean Water Act, Wetland Protection Act, Clean Air Act, and so on). Long-term integrity and flexibility to meet future missions is also an important aspect of consideration. Therefore, “indicators” of training suitability for a particular suite of training scenarios may not be the best indicators related to other indirect objectives associated with long-term sustainability, stewardship, or compliance. Thus, what is needed is a spatially and temporally integrated network of decision trees that are based on prioritized land-use expectations, current status, and ecosystem inertia that influences progress and sustainability. These decision trees should emphasize what is "lost" and "gained" by each local decision, and the collective implications of that decision at other spatial and temporal scales.

Prioritization of objectives is needed to avoid conflicting conclusions that may lead to different management plans. For example, a land-use action that is benefitial to an endangered species (e.g., burning or forest thinning for red-cockaded woodpeckers) may be detrimental toward other goals such as air quality, neo-tropical migratory bird habitat, and so on. However, this detrimental action may be inconsequential at landscape scales or extended time scales; in fact, auxillary benefits such as decreased wildfire risk, improved visiability for training, and improved habitat foraging & plant diversity may result from these actions in the long-term. However, in some cases, conflict caused by land management actions will exist; thus, require prioritization. The role for land managers is to provide prioritization, maintain consistency in decision-making toward these goals, and monitor progress toward well defined objectives. One role of research is to investigate tools and techniques that either accelerate progress toward a particular objective or increase "overlap" toward multiple objectives. A second role of research is to help define the resilience, magnitude, and variation of "overlap" between management objectives as well as investigate temporal and spatial thresholds that will limit unintended consequences of land-use actions. For example, is collective air quality less effected by burning using a particular technique or planning strategy (spatial, temporal scales); and do these differences lessen progress toward intended goals, detract from other secondary benefits (e.g., establishment of understory pyrophytic species, improved training visiability), or lead to new challenges (e.g reduced productivity, declining forest health, increased watershed runoff).

Multiple management considerations also confuse or lessen the value of indicators. For example, indicators of "training sustainability" are unlikely to be the same as those that indicate progress toward a forest management or conservation goal. Certainly, indicators of other land-use objectives such as watershed health, recreational opportunity, landscape pattern, ecosystem function, silvicultural health, and so on; would be equally varied as the land management objectives. In short, there is no “silver bullet” indicator or threshold that can meet all objectives, and for those identified by SEMP I research, most are only capable of addressing a limited number of land management expectations. Therefore, to allow for a weighted analysis approach, future evaluations and use of this data should emphasize the need to prioritize current and future-use objectives.

One problem with the SEMP initiative was limited consideration by both research and management as to the purpose of identifying indicators and prioritized criteria. This resulted in studies that were essentially independent and prioritized based on apriori insight of individual research groups. This approach resulted in studies that were not necessarily focused on current land management priorities. Further, the objectives and purpose of these studies focused on sustainability, thus failed to address compliance concerns. For example, based on personal knowledge of the development of the SEMP program, research groups were encouraged to look at potential issues beyond concerns associated with red-cockaded woodpecker recovery.

One collective outcome from the SEMP studies is that indicators are needed to identify both degradation and improvement. These indicators may or may not be the same parameter, or may require assessment at alternative scales. For example, available N is generally low in healthy upland forest ecosystems as well as seriously degraded ecosystems. In the former case, low available N is due to uptake and storage; while in the latter case, low available N is due to limited fixation and storage capacity or excessive leaching or soil loss. Similarly, individual biotic indicators such as species richness, species presence, or species groups have differential relationships with ecosystem condition or function. For example, one species or group may be highly responsive to degradation but have a slowed response to recovery, while other species may have a reversed relationship. Therefore, ecological indicators can not be used individually but rather applied using analysis that can detect collective patterning of ecosystem improvement as well as degradation. Obviously, a separate analysis and model is needed for each case, and likely driven by differences in ecosystem assembly and disassembly sequences and patterns. Some consideration should also be given to lagged-ecosystem response, particularly at larger scales, because of inherent temporal and spatial stochasticity that can “mask” change as well as ecosystem resistance that restricts change.

Literature review of indicators and thresholds

Since the mid-1980's, a series of research and review articles were developed to address a variety of environmental concerns; initially compliance or water quality related ecological threshold issues (EPA 2000). Many of the initial papers emphasized an "economist" approach with the intent of developing diagnostic tools capable of forecasting problems as well as evaluating the status and progress of environmental conditions. Various land management agencies (USDA, EPA, NOAA, USFWS, and others) began an evaluation of criteria and protocol that met the need of assessing respective national program objectives. One noteworthy initiative occurred during the mid-1990's, whereby the EPA developed a Environmental Monitoring and Assessment Program (EMAP) that focused on developing environmental indicators suited for local and regional scales of assessment. Many of these early indicators focused on the relationship between physical conditions (water-budgets, soils, topography, etc.) and environmental quality. The National Research Council (NRC) then released a report that reviewed and outlined national, regional, and local ecological indicators associated with terrestrial and aquatic habitats. Since the release of the NRC (2000) report, peer-reviewed journals have been developed that focus on ecological indicators (e.g., Ecological Indicators, Elsiever Publishing, Inc.), a series of other published articles have been released (Dale et al. 2002, Niemi & McDonald 2004) that have further refined or defined aspects of the recommended ecological indicators, other studies (Tilman et al. 1997) have indirectly challenged the value of particular indicators (e.g., species diversity), still others have suggested alternative criteria for consideration (Turner 2005), and a variety of papers have focused on other uses of ecological indicators such as species- or habitat-specific conditions (Niemi & McDonald 2004).

As a platform for comparison of the collective SEMP initiative, the NRC 2000 report will be used for comparison throughout this document. This report recommended the following suite for national consideration (NRC 2000, Chapter 4).

National indicators

The NRC report indentified **land cover** and **land-use** as the most important landscape features. Land cover is a critical aspect of extent and inherent connectivity, while land-use defines a suite of criteria associated with a particular category on the landscape. Historically, a variety of comparative studies have considered differences in water-budget, nutrient cycling, habitat-use, and the importance of connectivity and landscape arrangement that facilitates biological and ecological integrity of species and function. Consideration at the local level is important in evaluating changes in watershed capacity and process that may be associated with urbanization and land-use change as well as potential effects from climate change. Several studies have indicated the value of other landscape measurements and parameters (Dale et al. 2006, Turner 2005) to address specific concerns, but all are dependent on the two simple measurements; land cover and land-use. These same measurements are critical in evaluating species diversity (Rosenweig 1995) as well as settings for military training. Currently, the Fort Benning community is tracking these landscape parameters using a variety of satellite and aerial imagery techniques. Ongoing efforts continue to evaluate the frequency, timing, and cost effectiveness of these techniques to address a broad range of management concerns (sediment movement, habitat connectivity, watershed evaluations, training land suitability & sustainability, forest health & productivity, landscape scale C & N budgets). Relative to connectivity with national classification systems, NDVI classifications have been integrated with other internal (e.g., forest type classification) and external classification (e.g., TNC vegetation associations for Fort Benning) systems.

National and regional evaluations of "Ecological Capital: Biotic Raw Materials" should include the following indicators: **total species diversity** and **native species diversity**. At the local and regional scales, these efforts involve local, county and regional inventories of native species present, native species lost, and non-native species; and can be obtained through various sources such as Nature Serve, and through local sources of documented survey, inventory, and research information (TNC, GA DNR, USFWS, Fort Benning Conservation Division, SEMP repository, and others). Local tracking of the status and pattern of regional information is important in evaluating local risk of invasive species establishment because of the frequency and scale of disruptive disturbance on the Fort Benning and the elevated potential for invasive species movement with military equipment. Further, the potential influence of climate change in redefining habitat settings and ecosystem function have a higher likelihood of early expression on military landscapes because of the type and rate of disturbance. Therefore, movement and establishment of "new" invasives from Coastal areas onto the Fort Benning landscape have a much greater likelihood due to rearrangement of species assemblages and limited biotic exclusion of establishment.

Recommended evaluations of “Ecological Capital: Abiotic Raw Materials” should include **soil organic matter** and **nutrient runoff**. Estimates of soil organic matter represent soil conditions and the capacity to meet expected demands. In agricultural settings these “demands” are agricultural yield, in forestry and conservation settings these “demands” are sustainable forestry and the ability to achieve conservation goals, and in training land settings these “demands” are the ability to sustain and meet training requirements. Except in austere settings, periodic measurements of soil organic matter and nutrient runoff in areas with forestry and conservation goals are not generally valuable indicators because soil organic matter and nutrient runoff conditions are generally satisfactory or tightly controlled by ecosystem processes. Differences between locales are governed by inherent features and legacy conditions, but tempored by local carbon budgets associated with the existing and developing vegetation. However, at Fort Benning soil conditions should be monitored because of the impact of military training on carbon and nutrient cycling, as well as nutrient storage. Future monitoring of these metrics will provide a means of evaluating a landscape’s ability to meet specific objectives as well as an assessment of carbon and nutrient loading into down stream ecosystems and the atmosphere. An evaluation of soil organic matter will also serve as a platform for evaluating soil C storage if a national carbon credit system is developed to mitigate global increases in atmospheric CO_2 and corresponding climate change responses.

The issue of ecological functioning and sustainability should remain as a concern for Fort Benning for two reasons: (1) elevated impacts from increased training load, and, (2) limited coordination and overlap between sustainability efforts and objectives of the Land Management/Conservation Branches (DPW) and the ITAM/RCLA/LCTA programs (DOT). The former group is limited to sustainability concerns associated with compliance issues, while the latter group is limited to sustainability concerns directly associated with rangeland and training concerns. Therefore, a “gap” exists in addressing long-range suitability and sustainability issues for future-use, ecosystem function at broad-scales and across extended timelines, and the capacity to meet and overlap multiple compliance and training objectives that also extend beyond the current Fort Benning foot print.

Various aspects of ecological functioning and performance were identified by the NRC (2000) report.

These include; **production capacity, net primary production (NPP),** and **carbon storage**. Production capacity is essentially a measure of the landscape to capture and convert CO_2 to biotic forms, NPP is measure of the net efficiency of the process of CO_2 conversion across the landscape, and carbon storage is a measure of the retention and turnover of stored carbon. Again, local concerns of these metrics are relative to the direct and indirect impacts of training on process efficiency and capacity thresholds that can be detected at various scales by the loss of vegetation resilience and recovery; hence, rapid conversion to a inefficient ecosystem or abiotically-controlled barren ecosystem. Part of the evaluation of these parameters should consider the regional contribution of atmospheric carbon associated with burning to conserve, prepare, and maintain fire-dependent ecosystems. Generally, production capacity and NPP are considered to increase with burning, but associated losses of carbon through combustion may detract from this benefitial response by the existing vegetation.

Other recommended parameters for ecological functioning and permanence also include **Nutrient-use efficiency** and **nutrient balance.** These parameters are particularly recommended for agricultural systems; however, would have some value in locally evaluating heavily used training range areas that are devoid or partially devoid of vegetation. A great deal of emphasis has been placed on nitrogen budgeting as well as the influence of fire on nutrient-use efficiency and balance in southeastern ecosystems (Hendricks et al. 2002); however, some studies have suggested that N fixation rates in the southeast are great enough that P often becomes a limiting factor. Nitrogen is strongly associated with growth response and photosynthetic efficiency, while P is strongly associated with reproductive effort and efficiency. In heavily disturbed ecosystems reproductive effort by the persistent plants is equally important in the reestablishment of natural cover. Further, unlike N which can be atmospherically fixed, P cycling is very reliant on decomposition from surface organic material and extraction from sub-soil supplies. In severely disturbed areas, surface organic material (litter) is very limited and soil compaction restricts root expansion into deep sub-soils and limits surface soil exchange with deeper horizons. These severely disturbed areas may also have very limited microbial activity and efficiency which also impacts nutrient-use, storage, and balance. The lack of nutrient balance also seriously limits ecosystem function and efficiency. At the watershed-scale, unretained sources of terrestrial N and P pose serious threats to wetland and stream quality, as well as potential health concerns (e.g., nitrate, nutrient-induced algal blooms).

Stream oxygen is recommended for monitoring because of its influence on stream ecosystem functioning and habitat quality. Current measurements at Fort Benning suggest that stream oxygen levels are generally satisfactory except in small streams during drought periods. Anoxic conditions do develop in small watershed streams and are more likely to occur in heavily trained watersheds. Potentially, climate change may result in less frequent, more intense rainfall patterns which will result in great amplitudes of stream flow and greater likelihood of dried stream beds. Observationally, these dried stream beds are attractive to feral hogs, which unearth sediments and deposit fecal material. Both sediment and fecal material are then transferred during future storm events as well as increase biological oxygen demand, suspended sediment concentration, bed sediment instability, and fecal coliform risks. Though stream oxygen is important to stream function, other factors such as bed sediment stability, total suspended sediments, detrital organic material, and coarse-woody debris have been locally identified as being critical to stream quality. These factors are also well correlated with regional criteria for biotic integrity.

Impoundments persist across Fort Benning and are used for recreation and military training. These impoundments also serve as wildlife habitat and surface water catchments for stream sediments. Generally, **lake trophic status** is not well monitored but lake water quality is and important criteria in evaluating potential human health risks associated with training. From the standpoint of habitat and fisheries quality, submergent vegetation is periodically controlled using approved herbicides; though chemical control of lake vegetation is known to seriously elevate short-term biological-oxygen-demand during the decomposition of the resulting detritus.

This report recommends the following ecological indicators for local and regional consideration (NRC 2000, Chapter 5).

Local indicators

As a local measure of ecosystem productivity, the following metrics were recommended for monitoring: (1) **productivity and tree species di-**

versity, (2) **soils**, (3) **light penetration**, (4) **foliage-height profiles**, (5) **crown condition**, and (6) **physical damage to trees**. Measurements of some of these parameters are currently collected through the existing inventory process. A subset of the remaining parameters, as well as adjustments to the currently-used methodologies, could be added to the existing protocol.

Canopy productivity and tree species diversity at Fort Benning can be inferred through periodic forest inventories. Relative to productivity, measurements of stand level tree growth can be estimated through density-area relationships and diameter size. At broadscales, the current inventory methodology is sufficient to evaluate the relationship between landscape setting and canopy relationships. However, at local scales, such as those periodically used for training, more frequent and better designed monitoring is needed. Further, improved canopy measurements, and latter described species diversity indices, evaluation of land management effectiveness toward DFC goals would be improved.

Soil characterization and classification has been conducted at least twice in most areas of Fort Benning (USDA 1928, NRCS 1994, 1998). Soil characteristics can be used to characterize productivity using standardized forest productivity equations that characterize time-dependent growth, height, and timber volume profiles. However, portions of Fort Benning are characterized as anthropogenically disturbed soil profiles without soil relationships to productivity and ecosystem function. These same areas tend to be repeatedly disturbed, thus, merit periodic evaluation. Further, existing soil coverages have limited value toward interpretation because of legacy effects of training. Thus, local-scale characteristics are likely to overestimate ecosystem capacity and function. Though unknown, the effects of over-estimation is likely to be limited to small watershed units.

Light penetration is not currently evaluated. Some inferences associated with canopy closure can be made from canopy stocking densities and size-class information as well as LIDAR aerial photography. Light penetration and canopy openness is useful in evaluating disturbance recovery, forecasting understory and forest floor suitability for native and invasive species, and indirectly used to as a component of smoke and heat dispersion fire behavior models (e.g., BEHAVE: USDA-Forest Service 1999). The recommended technique by NRC (2000) is to use hemisphaerical photography, though low-cost techniques using densiometers are available and perhaps more appropriate for forest inventory field crews.

Foliage-height profiles are not being assessed to evaluate habitat conditions at Fort Benning. Vertical habitat structure and spatial patterning are strongly associated with micro-site conditions, local resilience to disturbance, and when effectively patterned, increases the range of habitat types and species diversity. Past installation-wide aerial LIDAR imagery at Fort Benning did not include the spectral ranges required to assess foliage-height profiles. As a demonstration project, foliage-height characterizations were attempted to characterize forest health conditions and the presence of invasive exotics (e.g., kudzu); however, limited success resulted (Ustin, pers. comm.). Field measurements associated with RCW habitat evaluations have included assessments of evaluations of understory coverage, composition, and understory size-class diversity. Future initiatives are currently considering improved field and imagery evaluations of understory foliage-height profiles as part of an assessment of remote forest classification, progress toward Desired Future Conditions, to estimate understory fuel type and biomass volume, and habitat characterization. As part of a related-SERDP funded project, sandhill habitat characterization and TES plant habitat suitability models using imagery- and ground-based information were successful for some species and habitat type settings (SI-1302, Sharitz 2006).

Recently adapted protocol to evaluate **crown condition** and **physical damage to trees** is being used for forest inventory and RCW habitat assessment at Fort Benning. The protocol is currently being evaluated to improve assessments of tree damage, species, disturbance history, and site index relationships with forest health risk. At the individual level, crown condition and damage type class is being evaluated, then collectively associated with tree-mortality relationships. Permanent plots are also being used to evaluate mortality rate. Currently, crown-class relationships with growth and productivity are not being made for most areas; in part, because trees with unhealthy crowns are being removed during the forest thinning process. However, additional comparisons could be made using existing data such as the growth of individual RCW trees and those trees associated with permanent Forest Inventory and Assessment (FIA) plots. Also, research plots are being used to assess forest health status and mortality rate.

The NRC report (2000) identifies three measures of species diversity that can be used as ecological indicators. These measures are based on traditional sampling protocol, however, are collectively interpreted using alternative methods to avoid bias assocated with sample size, sample period and duration, and dynamic processes that influence species count patterns. The well-reviewed, proposed indicators are influenced by conditions that regulate species-area relationships with emphasis on source-sink relationships (Rosenweig 1995) that occur under non-static natural ecosystems, local efficacy and system-dependent pattern of optimal dispersion (Tewksbury et al. 2002), and an evaluation of the depletion of species through the impacts of legacy and current anthropogenic influences, as well as the replacement of native species by the establishment of invasive species (Bohn & Amundson 2001).

Application of the proposed species diversity indicators poses two primary challenges in interpretation and calculation when applied to plants in a fire-adapted environment. First, as proposed by Tilman et al. (1997), many plant species effectively perform the same function; therefore, functional species diversity is a more appropriate metric to minimize the importance of similar species. If Tilman et al. (1997) concepts are accepted then individual species should be weighted differently based on their functional importance. There is some value in this concept, particularly if any particluar landcover is expected to meet well defined objectives that can be value-based, therefore, “weighted” to assess the contribution of a species toward a series of well defined objectives. The premise of these indicators would remain based on power-law relationships; however, multipliers for each species or functional guild would be needed. For example, if an objective was to provide a variety of fructose-based soft-mast during the summer months for songbirds, Rosaceae species would have greater “weight,” or value, than those in the species in the Poaceae. Though difficult to define, purpose-based analysis of species or functional diversity could be achieved with slight modification of the proposed ecological indicators.

Secondly, many plant species are highly reliant on asexual regenerative sprouting and have extended longevity; therefore, an “individual” is difficult to define relative to species-density relationships, and differences in life-cycle duration add complexity to interpretation. Unlike fauna, which have a strongly skewed negative logistic relationship when the number of species or individuals is plotted against average longevity; thus, any lag effect caused by the limited occurrence of long-lived species is minimized.

In the case of flora, the relationship is less skewed towards shortened longevity; therefore, persistent occupation and prolonged influence on ecosystem processes is much greater and less responsive to isolation. For example, within fire-maintained habitat strata, annuals co-exist with long-lived perennial forbs & grasses, as well as even longer-lived woody sprout species. Annuals are responsive to criteria associated with that given year, while the presence of long-lived sprouts responsive to a life span of cumulative influences and may be uninfluenced by isolation.

Certainly, an analytical response to this dilemma is to consider an integrated solution that accounts for all differential longevity-classes; but species-specific age-structure characterization becomes difficult because above-ground age classes in a fire-prone setting are unlikely to match below-ground age classes. Certainly, age-class characteristization is potentially destructive and labor intensive; thus, such an approach would be beyond fiscally-limited monitoring efforts. A much better approach is to apply the suggested matrices, yet understand the potential limitations of the interpreting the proposed ecological indicators.

Indicator of independence (I_i)

$$I_i = [\log S_w - \log S_i] / 0.2 * [\log A_w - \log A_i]$$

where S_w = (species richness or estimate within province area), S_i = (species richness within area of interest), log A_w = province area (e.g., Chattahoochee fall-line sandhill region), log A_i = area of interest (e.g., Fort Benning), and 0.2 represents .a threshold associated with the local occurrence of “sink” species (Rosenweig 1995, NRC 2000). Interpretation of I_i, based on NRC 2000 report, suggests that values greater than 1 indicates that few “regional” sink species contribute to the overall richness; therefore, local species diversity is independent of connectivity. If I_i is less than 1, “sink” species do contribute to overall richness through some level of connectivity to the remainder of the region. To use this ecological mononitoring index, repeated inventories may be needed to capture all occurrences. To develop regional and province area information, various resources can be used such as NatureServe (2007), State & County surveys, as well as other interactive software resources.

Indicator of species density (D_i)

$$D_i = S_i / A_i^z,$$

where S_i = species density (richness) within a given land cover type, and A_i^z = area of a given land cover type in which i represents a particular land cover type and z an exponent that linearizes the relationship between species richness and area (Rosenweig 1995). Therefore, D_i represents a linearized species density estimate for any particular landcover. A cumulative species density estimate for all landcovers can then be made through the the following equation:

$$D = \sum (D_i * p_i)$$

Where p_i represents the landscape fraction or proportion for a particular landcover (i). However, to evaluate landscape change, differences in (z), the exponential weight that linearizes the species-area relationship, between land cover types must be considered. For example, to evaluate the conversion from forest to open training range; two relationships require consideration; differences in (z) and differences in S_i / A_i relationships between landcover types. Based on Rosenweig (1995), differences in (z) are minimal and generally assume a value at or near 0.15; however, S_i / A_i relationships require correction because within habitat species-area relationships differ with landcover type. These differences can be comparatively accounted for by using ratio-based relationships when a finite unit of area is used.

Also, as a precautionary measure, before accepting the assumption that differences of (z) are minimal between landcover types, an estimate from severely disturbed landscapes should be made and then compared to other landcover types.

Currently, satisfactory information is available from various Fort Benning studies to evaluate particular landcover types. To date, few studies have characterized heavily manipulated habitats and wetlands. However, simple comparisions could be made for some upland landcovers; for example, trained areas could be compared to existing reference areas, comparison species-area patterns of heavily and lightly trained could be made, and so on.

Indicator of deficiency in natural diversity (U_i)

$$U_i = [\, cA^z - S_{i,n} \,] / cA^z ,$$

where cA^z = the number of species expected to occur in a finite area, and $S_{i,n}$= the number of observed native species in a finite area. This approach provides a fractional comparison of observed species richness within a given area of a particular landscape and then values this condition based on an expected species richness pattern (cA^z). Careful estimates of cA^z can be made using reference sites or documented areas of high quality land-cover. When a collection of reference sites that typify an average condition, then the comparisons are made relative to a baseline condition and useful in defining whether a particular site is above or below the norm. When observed patterns are compared to high quality sites (defacto Desired Future Conditions), then an assessment of progress toward those conditions can be made. Finally, when reference sites that represent the normal or typifying landcover condition are compared with high quality sites (or even literature-based projections of DFC's), then an assessment of overall land-scape progress toward the conditional DFC associated with a particular land cover can be made. As previously mentioned, this ecological indicator can be modified using value-based species weights if particular objectives are desired. As an example, if the primary objective for a particular land-cover is to develop a diverse understory dominated by fire-tolerant grasses, species weighted adjustments can be made.

Fort Benning is currently using a form of the **Stream index of biotic integrity (IBI)** that is based on rapid biological assessment protocol. The method used is weighted toward preferred functional species groups that represent good quality stream habitats. These sample methods are deployed during a seasonal period of low year to year variance (autumn), sampling initially involved quarterly assessments and then was adjusted based on variance pattern. Stream indices of biotic integrity collectively reflect functionality (e.g Carbon resource conversion and storage) as well as stream condition. Future improvements should include greater comprehension of the role of CWD, bed sediment stability and composition, sediment loading, concentrations of total suspended solids, and hydrologic flux and pattern as well as expanded estimates of frequency and stability for "riffle," "run," and "pool" habitat along stream segments. At the watershed scale, improved estimates of anthropogenic features (e.g., road density, crossings, etc.), land-use type & pattern, as well as wetland type, quality, and function are also needed.

SEMP indicator and threshold evaluation

Potential indicators and thresholds can be evaluated using a variety of criteria; cost, adaptability, variability and scale, predictability, and applicability to regulatory requirements and military training. Some of these same factors were used by Dale (SEMP Integration Report, 2006). Because most of these variables are qualitative, multivariate comparisons evaluations were made using various multivariate techniques. These techniques categorize the various parameters based on similar traits as opposed to correlative relationships. The latter condition can be assessed using multiple-scale path analysis, those techniques described by Dale (2006), other multivariate techniques (e.g., Discriminant Function Analysis), structured equation models that are priority based, or alternative decision based approaches such as Bayesian belief networsks that emphasize priority through structure, and strength of assumption (Dennis 1996, Hara et al 2002, Clark 2005, McCann et al. 2006, Radtke & Robinson 2006).

Beyond suitability and effectiveness of measurements, the development of a monitoring plan also must consider timeliness of the information, cost effectiveness within budget guidelines, adaptability of information to future concerns, and application to current and future compliance and regulatory issues. Though performance of this step is a critical component of developing cost-effective indicators, prioritized guidance of land management and conservation objectives is needed. Selection of indicators and methodologies solely based on cost efficiency without considerization of risk and priorities would be very near-sighted because cost-efficient, but unnecessary, measurements would likely become imbedded within the monitoring program, and potentially exclude more valuable measures.

Cost reflects both the numbers of samples required to sufficiently address monitoring concerns, as well as the cost per sample. Indirect costs should also be considered, and include equipment start-up costs, specialized training, equipment maintenance, reagents for chemical analysis, specialized safety requirements, and equipment associated with improved sample care and treatment. Independent of sample analysis and collection, cost is a function of the number of samples needed based on the expected level of variance (spatial, temporal, replicates) associated with a standard sampling scheme that would properly reflect conditions within a meaniful area. Because training, land management, and other army associated practices tend to be at a wide range of scales, estimating appropriate techniques for assessment can become a challenge.

An additional direct cost component is "cost per sample"; this should be inclusive of labor requirements as well as cost associated with processing, analysis, and interpretation. Variable components to consider include "local travel cost" between sample locations (e.g., installation wide sampling efforts result in the labor force spending a significant portion of their time in the vehicle) as well as the frequency of sample visits to the same sample locale. To date, very few studies and assessments have evaluated "sample cost" as a component of risk analysis and assessment nor have these concepts been built into local military planning. Further, direct measures of "risk" and risk likelihood are often very limited.

Adaptability reflects the relatedness to what is already being collected and what needs to be collected to address future concerns. Also, whether a new variable could be added to an existing sampling scheme, or a new set of skill mixes and equipment would be needed (e.g., microbiologist, chemist). An assessment of variability and scale is inclusive of the sampling intensity required to represent spatial and temporal patterns of indicator values.

An assessment of predictability is inclusive of the strength, breadth, and type of relationship between the indicator variable and the influencing disturbance factor. Obviously, the strength of the relationship is reflected by the statistical predictability, and the breadth of the relationship refers to changes in the strength of the relationship at or near end point conditions. The type of relationship influences the interpretability of the indicator. Direct functional relationships are obviously the best in explaining the causal relationship between action and response; however, strong correlative relationships can be equally valuable if they are more timely, more appropriate to scale, easier to assess, or less influenced by other processes. Finally, predictability is inclusive of the timeliness of detecting an indicator response, a lagged functional response or strong correlation may be perfectly suitable for posterior evaluation, but poorly suited to initiate proactive responses to mediate potential environmental problems. Therefore, a suitable indicator must predict a problem within a timeframe suitable for response. Further, sampling strategies must be appropriate for the same purpose.

Applicability to regulatory requirements and military training is a critical level of assessment because emphasis will always be placed on those factors associated with the regulatory process. Unfortunately, ecologically meaningful parameters are often not the same factors that are assessed during the regulatory process. In fact, those factors assessed during the regulatory process tend be posterior response to the same ecologically meaningful parameters. Therefore, the applicability of predictive indicators can be a measure of its stepwise relatedness through a known cascading pathway. For example, forest health influences net forest production; hence, tree growth, insect productivity, needle cast litter fall, and shading of understory plants; all of which in turn, influence fire behavior. Both insect productivity and type as well as fire behavior affect RCW diet and habitat. Using a similar metric, forest health directly influences mature tree mortality rates, mature tree mortality influences RCW cavities and suitability for RCW colonies. In this example, the latter is obviously a more direct relationship that is narrowly focused toward RCW needs and less focused on ecosystem process. Therefore, each indicator needs to have a conceptual crosswalk from ecosystem process to regulatory concern or training land sustainability (RTLA program); and in some stepwise manner its relative contribution toward an assessed “at-risk state.” Such an assessment, due to limited quantitative information but extensive qualitative insight, would likely be best addressed using a Bayesian approach that weighs data equally with logic-based knowledge.

Overview of collective findings

All or most of the research groups observed the similar patterns; for the most part, these patterns were expected and consistent with other findings (NRC 2000). Military training influences ecosystem patterns by resulting in the loss of vegetation structure. Negligible, but potentially incipient, loss is associated with single event disturbances involved in dismounted training (e.g., orienteering). After years of training most low to intermediate intensity training areas have between 5-50% of the forest floor disturbed beneath a complete to partially broken canopy. Most of the disturbance scars are “inactive” and associated with tracked vehicle movement and are particularly noticeable in clayey soils. All of the research groups found soils with more sand (>70%) and respond differently than those with less sand (<70%); however, soils with clayey A-horizons were not distinguished from those with exposed clayey sub-horizons and parent material. Hence, the observed patterns may as much reflect precipitated effects of past disturbance as well as differential responses due to textural differences.

Soil compaction and A-horizon loss have many negative impacts on ecosystem processes including: reduced seed germination and root growth, retarded aeration and water infiltration, increased runoff and erosion, decreased microbial activity and nutrient dynamics, increased difficulty in invertebrate and vertebrate burrowing activities, and discouraging the development of biologically active surface crusts and litter mixing. The loss of watershed capacitance also impacts stream hydrology as well as stream habitat characteristics. Interestingly, comparison of compaction values from the various study groups indicate similar values for heavy and intermediate-use areas but more variable values for less impacted areas. Reddy (2005) found that Fort Benning has greater overall compaction relative to nearby locations. This finding likely reflects legacy land-use effects. Other studies have found similar patterns in areas converted from intensive agriculture to reforested longleaf pine forests (Markewitz et al. 2002). This study also found similar patterns of surface soil movement, soil carbon, and nutrient reserves.

More significant disturbance was observed in areas with mechanized training (tracked, wheeled) and recent land management activity (wheeled harvest equipment). One noted difference, was that forest management activity appears to facilitate recovery toward an equal or better state or condition. These disturbances were particularly magnified and cumulative in heavily used areas, whereby insufficient time exists between training events for partial or full recovery. Several researchers noted that recovery was particularly slow or reversed on clayey soil sites, sites that were repeatedly disturbed or burnt, and in areas with limited carbon input. In some cases, disturbance resulted in potential nitrogen excess due to Carbon limitations; in other cases, disturbance combinations resulting in limited mineralization and potential N deficit. The loss of vegetation directly and indirectly impacts other ecosystem processes that include:

- Vegetation loss results in lost interception of precipitation, which results in increased input into the soil and increased soil surface interception energies that lead to fractured surface structures and movement with water. Forested areas intercepted near 20% of the precipitation from most storm events, while open ground areas intercepted 2-3%. The intercepted water was returned via evapotranspiration without contact with the soil surface. Of the remaining water, 10-15% was slowly released to the soil via stem flow along tree branches. Unmeasured but documented elsewhere, is the impact of stems on surface water flow, full vegetation coverage greatly restricts water movement energies due to frequent contact, altering patterns of cohesive and adhesive water bonding, and constant interference with differential energies associated with laminar vs. linear surface flow relationships.

- Vegetation and plant litter loss results in increased incidence of "soil crust" development. Soil crusts are thought to be derived through bacterial activity at the soil surface, and serve to influence rhizosphere gas exchange relationships. With low moisture deposition, morning dew or light rain, these crusts are functionally hydrophobic and prevent water adsorption into the soil surface. Though low in concentration, low precipitation and deposition have been shown to be critical sources of moisture for young and developing seedlings during the summer months.
- Vegetation loss results in a lowered capacity of naturally recovering from anthropogenic soil change. Soil maturation and development are equally influenced by biotic and abiotic processes. Root growth and soil invertebrate activity are critical processes for loosening soil, incorporating and contributing organic material to below-surface depths, and increasing the depths of biologically active soil.
- Removal of vegetation results in lowered evapo-transpiration and evapo-transpiration demand. Within the Coastal Plain, plant water-use is 2-3 times potential evaporation rates, the result is a collective "drag" on soil drainage and an increase in water residence time; hence, slowed transfer of water toward wetland systems and extended stream volume response
- Loss of vegetation cover results in increased soil temperatures. Increased temperatures affect activity rates of soil surface processes, both directly by accelerating activity and indirectly by accelerating water loss causing biological inactivity for some species. During summer conditions following a typical precipitation event and without additional input, rhizosphere activity extends for about 2-7 days in areas with exposed soils and 6-10 days in forested soils. Obviously, with a precipitation pattern roughly once a week, exposed soils are potentially inactive during a significant portion of summer days.
- Removal of vegetation, or losses in productivity and decomposability (e.g., heavily lignified), leads to a decrease in organic input and mineralization rate. These changes cause shifts in C:N ratios and process efficiency within the rhizosphere. These changes also result in change in nutrient availability and resource holding capacity (moisture, nutrients).

- Loss of vegetation results in significant changes of biological habitat quality and proportion. These changes result in shifts in habitat type, as well as responding species population and resulting ecosystem efficiency, sustainability, resilience, and resistance to anthropogenic change. The change in habitat type and quality is initiated by changes in plant community and productivity and quickly cascades into changes in other biotic guilds (insects, bird, etc.).

Changes to soil conditions result from mechanized training, wheeled vehicle activity, or frequently repeated foot traffic. Soil compaction, surface soil loosening, and soil mixing are common results of these types of training or land management activities. Single events of activity result in these types of disturbance, but repeated events result in magnified conditions that are less likely to recover without remediation. Outside of the factors associated with vegetation disturbance, additional impacts include:

- Compaction of sub-soil reduces drainage & permeability, gas exchange, and watershed capacitance. Loss of permeability results in proportionately greater amounts of surface water movement and adsorptive loading within the surface soil, which is then collectively exerted upon microsites with fractured or lower sub-soil relief. The collective reduction in watershed capacitance to retain water results in accelerated movement of water into and across riparian areas; hence, increased response-time and amplitude of response in surface water flow volume and velocity. This can result in increased bed-sediment movement and stream bank erosion.
- Compaction results in root damage. The level and proportion of root damage cumulatively impacts plant and tree health as well as susceptibility to other pathogens and disease. Further, limited gas exchange, through compaction, forces root growth into surface horizons which increases the susceptibility to fire damage and drought, hence, increased fine root loss and health risk.
- Surface soil mixing and loosening results in the loss of biologically-active organic material and the sequestration of sand-bound colloidal clays that, upon disturbance, “migrate” through suspension to depths of reduced permeability (such as compacted horizons). This results in further advancement of lost permeability.
- Incipient land-use scars are known to have long lasting, derogatory impacts on soil productivity. These affects have varied impacts on biotic and abiotic processes. Ruts channel water movement, exposed

soils are opportunities for invasive species, and mixed soils reduce rhizosphere efficiency and conservation of limited resources. Historic soil compaction is also slow to recover, and affects resource-related and biotic processes.

- With expanding scale, the collective affects of vegetation loss and soil disruption may result in increased environmental risk, lost sustainability, lost ecosystem efficiency, and greater influence over terrestrial-wetland-stream interactions and processes. These influences may be further advanced by the effects of past land-use (e.g., 19^{th} century agriculture) and may result in the following:
- Results indicate that historical land use continues to influence important physical and chemical variables in these streams, and in turn, possible biota. Loss of stream integrity and ecological services may lead to stream impairment. Because of impacts on multiple levels of the ecosystem, stream recovery would likely require significant time and investment to restore necessary watershed functions.
- Interrupted or simplified ecosystem processes detract from resource use efficiency which effectively reduces overall ecosystem integrity and productivity, and facilitates "leaky" relationships with coexisting processes and ecosystems (e.g terrestrial to aquatic processes). An example that could develop with intense disturbance are imbalanced proportions of C:N or N:P that may result in the transfer of excess forms (e.g., nitrate) that are typically tightly conserved.
- Changes in terrestrial water residence time results in shifts in hydrologic response as well as corresponding shifts in stream habitat characteristics and regulating ecosystem processes. With decreased water residence time, four parameters associated with hydrologic response are adjusted: (1) initial time to response to a storm event is shortened, (2) amplitude of response is magnified resulting in greater volume and stream energy, (3) rapid recline to base flow levels following the storm event, and (4) lower base flow volumes. The result of the first condition is greater inertial energies that loosen standing sediment. Greater storm event amplitude results in increased volume and rate as well as channel flow which causes increased sediment movement rate, particle size, and transfer distance. Finally, lower base flow allows for greater potential of stagnation, dry down, and deposition of fine material within "riffle" as opposed to "pool" segments. Again, altering the stream bed diversity which is directly related to benthic invertebrate diversity and long term stream efficiency.

- High levels or sustained disturbance can result in accelerated down slope erosion and sediment movement into adjacent wetlands, riparian zones, and streams. The increased sediment input results in unstable stream bed conditions with resulting losses of coarse woody debris and other organic material as well as changes in stream profile, flow patterns, and stream bank stability.
- Increased sediment input results in lost coarse woody debris. Coarse woody debris serves as a barrier to bed sediment movement, habitat for a wide variety of invertebrate groups, and a chemical sink for mineralized nutrients. Buried coarse woody debris has reduced habitat effectiveness because of further reduction in gas exchange and increased reduction reactions.
- Increased sediment input also reduces the effectiveness of riparian zones. Small stream riparian zones are poorly suited to frequent deposition and removal of sediments. These systems are poorly adapted to small rates of deposition because of its influence on root process dynamics. Overall, deposition results in reduced riparian health and reduced resistance to stream bank loss. The loss of riparian vegetation results in increased flow rates within flood zones and additional transport of organic and fine sediment material as well as additional burial of vegetation with coarse sediments.
- Increased concentrations of total suspended solids (TSS) results in increased chemical loading and conductivity, decreased water clarity and acidity as well as increased risk to filter feeding invertebrates such as rare mussels and clams.

Not surprisingly, the past 150 years of land-use and ownership has led to dissection of habitats, reduced connectivity, and fragmentation. Nearly 90 years of adjusted placement of military-use and associated protocol has further fragmented today's landscape. Generally, the forests have comparable ages, most being established post-WWII and at coarse-scales have high levels of connectivity. However, adjusted and new placement of activities threatens to further dissect the landscape. Fine-scale fragmentation is high, this was documented using remote imagery by Dale (2005) and field analysis by Kryszik (2005) and Collins (2005). Improved connectivity and reduced fragmentation can be achieved through reduced densities of roads/trails/paths as well as continued emphasis on a matrix of compatable upland pine and mixed forest systems.

Finally, all of these processes can result in collective disruption of regional exchanges and functions associated with water quality, stream quality, net productivity, conservation of habitat and limited resources (C, N, water), and heat storage or capacitance.

Importance of hydrologic pattern and process: The influence on stream habitat and water quality

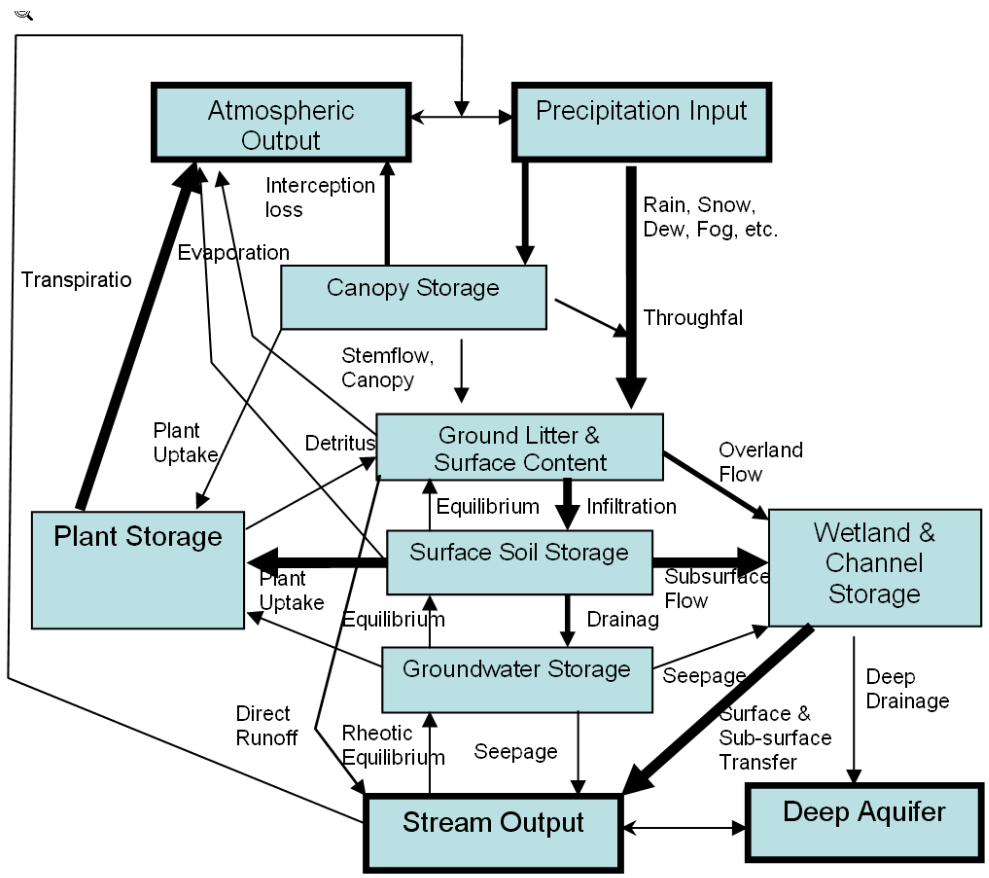

Figure 66. Hydrologic pathway.

As indicated by the figure above (arrow width reflects importance), the relationship between terrestrial land-use and its impact on water quality and water flow conditions can often be complex and governed by collective and lagged responses within a watershed catchment. These relationships include forest management decisions. As most know, inappropriate timing of management actions can compound existing problems or increase the likelihood of problems; thus, most timber sales and other management actions have built in requirements and restrictions associated with the logistics and timing of activities (e.g., KBDI, pre-planned haul routes, BMP's, water-bars, herbicide-use restrictions, etc.). However, these "safe guards" usually don't consider cumulative or residual effects that may be associated with other land-use activities (e.g., mechanized mounted training) in the past, future, or in nearby areas.

Countless studies over the past 30 years have emphasized the importance of full canopy coverage and species selection in regulating watershed behavior. Namely, fully stocked forested stands have much greater influence on watershed regulation than do understocked stands. Proportionately greater amounts of forested area yield reduced stormflow amplitude and elevate baseline levels due to the release of residually stored water. Finally, at similar basal areas, pine forests have much higher water-use than mixed or deciduous forests because of reduced water-use efficiency and higher leaf area index. Few studies have addressed the importance of understory cover or have attempted to quantify hydrologic differences between fully stocked mixed or deciduous forests and partially forested pine savannas, nor the impact of mid-rotation conversion from one system to the other.

Stream flow is strongly influenced by watershed storage capacity and inplace useage. Storage capacity is influenced by various surface and subsurface gradients that are dependent upon features that control drainage and surface movement such as soil textural profile, topography, surface flow resistance, etc.. Inplace water use is dependent upon season, atmospheric vapor pressure gradients associated with evaporative rate, and vegetation characteristics that define water-use such as vegetation type, biomass, water-use efficiency, and activity. For example, mature broadleaf deciduous forests can use 3-4 times than evaporative volumes, closed canopy young pine plantations up to 7 times the amount, pasture slightly more than twice the amount, and cropland is only slight more than what would evaporate from bareground conditions (Vose & Maass 2001). Further, these vegetation types have different interception rates that influence the amount and rate pattern of precipitation that reaches the forest floor (Oren et al. 1998, Liu 1998, McNulty et al. 2004). The collective influence of vegetation results in differential patterns of watershed scale water-use. This is noteworthy because land-use decisions could theoretically be made to redue erosion and sedimentation risk.

Streams associated with distressed watersheds tend to have highly fluctuating patterns of waterflow; whereby, higher short-duration amplitudes of flow rate and volume follow storm events, and much lower flow volumes between storm events. Further, stream flow associated with distressed watersheds is strongly influenced by seasonal and year-to-year weather patterns (e.g., drought).

Because of the amplitude of storm associated stream flow patterns, the likelihood of bed sediment movement is increased as well as associated particle size. Further, the storm flux also increases stream bank erosion, which contributes “unwashed” sediment into the stream. A common stream water quality problem is suspended sediments (clays, FOM) associated with base- and storm-flow. Instability of bed sediments and elevated suspended sediments also detract from habitat quality for various stream invertebrate groups.

The source of these sediments is dependent upon various factors that regulate watershed dynamics (land-use, transfer rate, water-use, road crossings, etc.), stream channel profile (stream legacy, bed sediment stability, flow capacitance, braiding, channel shape, overflow floodplain characteristics, etc.), storm characteristics, as well as profile characteristics of input, bank, and bed sediments.

A critical and often overlooked feature for evaluating suspended sediment risk is the differentiation of sediment source and input rate. Surface stream bed sediments are generally “washed” with coarse textured surfaces; therefore, contribute little suspendible fine material during base flow conditions. Sub-surface bed sediment textures are dependent on textural rate of change. Streambank sediment types vary because of various factors, and their contribution during storm and base-flow periods is influenced by variability in water flow volume and pattern that define erosive “forces,” bank stabilility, and texture and contributions of fine-sediment discharge is related to flow pattern. Streambank sediments of “pristine” watersheds are finer textured, those with extensive past-use will often be coarse textures that hide “buried” profiles. Lastly, erosive inputs have textures that reflect their local upland source. All things being equal, streams at the most risk of exceeding suspended material TMDL thresholds are those with high erosive input from fine textured soils within watersheds that have limited use histories and fine-textured streambanks with “V-shape” stream profiles.

Biological oxygen demands (BOD’s) and low flow rate, potentially due to limited watershed storage, influence water chemistries through reduced oxygenation. Also, continued sediment movement and water oxygen levels during low baseflow periods often limit biotic composition, particularly bivalve species. These species are particularly affected due to limited mobility, very low upstream migration rates, and complex reproductive cycles. Based on SEMP studies, most stream segments at Fort Benning do **not** have oxygen limitation problems. However, during periods of drought, those streams dependent upon on surface and sub-surface input can develop anoxic conditions in some sections. Overall, the SEMP studies found that stream chemistries, temperature, and oxygen level do not appear to be direct problems for larger streams. Water acidity, suspended sediments, and buffering capacity are adequate to support existing biotic communities but the values are not consistent with blackwater streams elsewhere (Mulholland et al. 2006).

Collectively, watershed risk can be categorized through unique combinations associated with the following questions:

- Is the watershed expected to have significant change in land-use and is this land-use concentrated within a particular drainage?
- Is the watershed characterized by high gradient, dendritic patterns of drainage or shallow gradient characteristics?
- Is the terrestrial watershed and stream banks characterized by fine textured surface and sub-surface material?
- Does the watershed have a history of intense use and past erosion/sedimentation; thus, have less stable conditions due to legacy land-use?
- Is the watershed heavily used with a significant amount (> 15%) of permanently exposed/altered drainage watershed area?
- Is water flow within the stream primarily governed by “ground-water derived spring flow” or surface and sub-surface runoff?

Relative to suspended solids, the most “at-risk” systems are those that have higher gradients, fine-textured soils, limited past-use but a projected change in land-use that would result in a significant portion of the watershed permanently exposed. Historic land-use and fine-textured soils equate to elevated stream bank erosion and channel cutting. The lack of cover results in increased surface and “rill” erosion, reduced storage capacity, and reduced rainfall interception.

In comparison, another “at risk” system has shallow gradient streams with coarse-textured soils, intense land-use histories, and limited cover that results in flashy hydrologic patterns and unstable bed sediment sands.

Therefore, each of these issues poses different watershed management challenges, and likely will require unique mitigation approaches.

The concept of "risk" can be defined in a variety of ways, e.g., (1) stream bed sediment instability and movement, (2) biotic suitability and sustainability, (3) suspended sediment loading, (4) chemical storage and process efficiency, and others. These various factors should be assessed in light of prioritized ecological services such as providing municipal water supply, sediment catchment, flood control, fisheries support, recreation support, aquatic habitat, chemical retention and storage, biological cleansing, etc.

Maintenance of water quality, wetlands, and watershed services

Based on SEMP findings, exposed areas are subject to erosion because they are without precipitation interception, they have crusted, partially impermeable surfaces, and are without vegetation that provides resistance to surface water sheet flow. The lack of vegetation cover accelerates drainage from the rooting zones, and results in reduced residence time. Further, these areas have limited perculation because of compaction, and limited storage capacity due to soil loss.

Identified stream quality criteria include bed sediment stability, expected hydrologic response to storms, and benthic dominance by POM-dependent species such as EPT. Midge fly (Chironomid) species occurrence and diversity are also indicative of biotic quality but are capable of rapid shifts in composition with changing conditions. Algal communities are not a specific indicator under typical stream conditions, but other studies. Consistent with NRC, 2000 SBI (Stream Biological Index) and fish communities were also found to be a good indicator of stream health. To facilitate dominance by EPT and associated species, sufficient organic material in various forms is important. The most lacking component in biologically stressed streams appears to be coarse organic material such as logs, branches, etc.

Fractional EPT composition is also recognized as a stream quality indicator by GA EPD. Current GA EPD efforts are to transition from SBI to Rapid Biological Indicators (RBI) that emphasize aquatic macrophytes. This transition will involve more frequent assessment (5 year as opposed to 10 year cycles), inclusion of smaller streams that have limited vertebrate occurrences, greater focus on species (macroinvertebrates) that more rapidly respond and recover to changing stream conditions, and are less impacted by prolonged impacts of periodic drought or other structural impairments (dams, etc.).

Hydrologic response to rainfall events is influenced by a variety of factors including stream specific conditions and profile, terrestrial land-use, as well as road crossing frequency and density. The various SEMP studies suggest that streams are significantly impacted when terrestrial land-use associated with open areas on slopes greater than 3% (including cumulative road area) is greater than 12% of the landscape. Based on these studies, this amount of open area accelerates water movement from the terrestrial landscape towards the stream at a rate that may exceed the capacity for the BMP or management defined riparian area to sufficiently protect stream water flow. These studies also indicate that high frequencies of stream crossings as well as road/trail densities accentuate the impacts of open areas. Unfortunately, these attributes are strongly correlated (heavy-use equates to high road density to access the areas and more frequent crossings) and increase erosion risk.

Indirectly, changes in stream conditions are consistent with changes in water chemistry due to reduced effectiveness of riparian zones and increased terrestrial movement of mobile chemistries associated with terrestrial land-use. Within limits, streams and riparian zones have the capacity to store and adjust to modifications to terrestrial land-use; however, when these changes become predictable they equate to changes functionality with new species guilds and habitat attributes. These changes in heavily used watersheds are less noticeable because change has occurred and more noticeable in “dormant” or susceptible watersheds (e.g., those with fine textured soils). Detection of continued change and degradation in heavily-used watersheds remains a challenge because of inconsistent response to weather patterns and waterflow.

The greatest current risk to Fort Benning streams appears to be sediment movement and sedimentation. To effectively evaluate the risk, some knowledge of input source is needed as well as stream profile characteristics. Sources of concern include the stability of stream bed sediments, the stability of bank sediments, and direct rill and surface erosion inputs into the stream. These risks impact both the biota, as reflected by rapid bioassessment protocol, as well as total suspended sediment (TSS) inputs toward the Chattahoochee drainage and coarse sediment movement that impacts habitat and flow pattern. Aquatic habitat quality and stability are strongly affected by TSS and coarse sediment movement because biota is directly affected by siltation and habitats are buried by coarse sediments. A current concern is what artifacts of past land-use sedimentation patterns still persist, and how does current land-use affect the stability of these sediments.

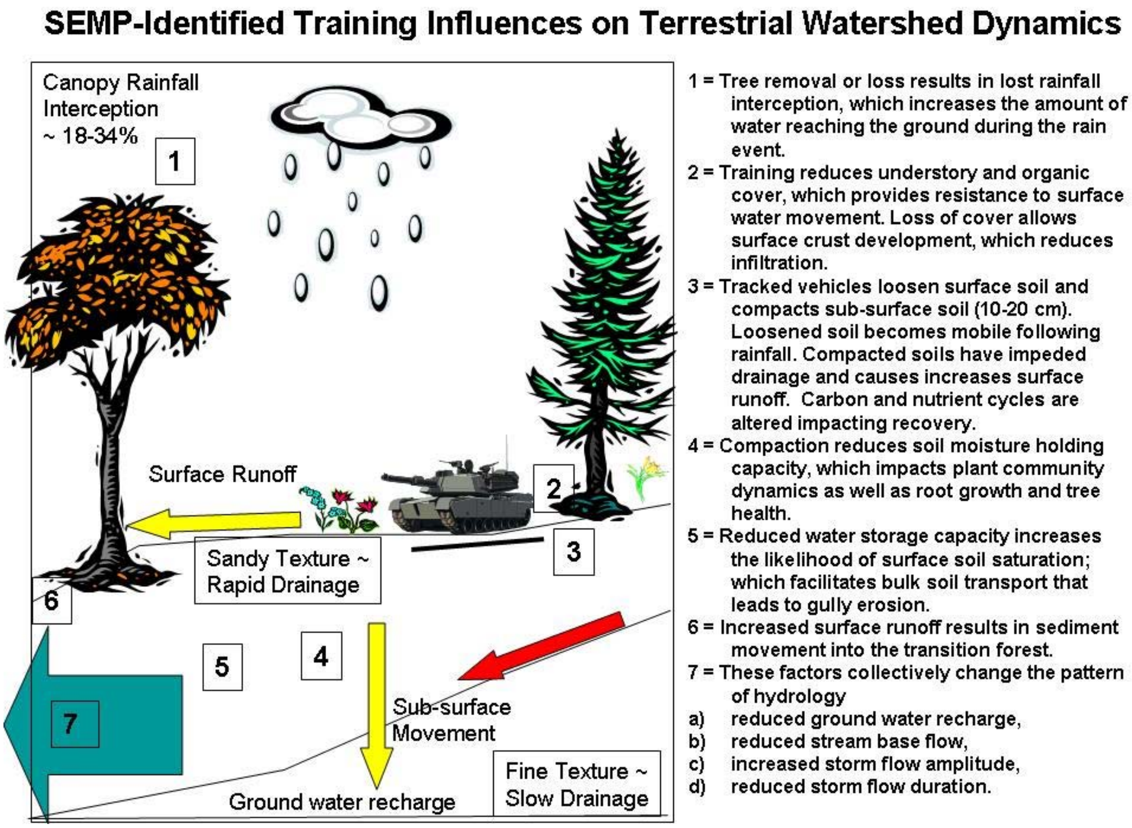

Figure 67. SEMP-identified training influences on terrestrial watershed dynamics.

The influence of inherent conditions and land-use on sediment movement and soil productivity

Military training increases the potential for erosion because of increased: a) magnitude, depth, and thickness of compacted horizons, b) loss of surface roots, c) loss of canopy, and d) loss or realignment of ground surface cover. Each of these factors result in reduced water residence and storage or increased rates of water movement following a precipitation event. Increased erosion is due to increased kinetic energies that are capable of loosening and carrying soil particles. Once in suspension, small concentrations of soil particles increase the abrasive forces associated with water movement and cause additional particle displacement and movement. At high concentrations, near the capacity to carrying capacity for suspended material, velocities are slowed by reduced viscosity (also increased specific weight) and heavier particles are then lost from suspension and replaced by equal volumes of fine materials. The end result is charged fine material is usually removed from the source of origin leaving behind unconsolidated and unstructured sands that during future events will continue to migrate down slope.

The level and influence of soil compaction on ecological processes, and associated biological response, are strongly dependent on; a) soil characteristics and properties, b) the type and duration of past and current use, c) spatial scales, and d) landscape setting. Important considerations when assessing compaction is the depth, magnitude, and thickness of the compacted horizons. Compaction at shallow depths is more likely to result from repeated use. Repeated use is also likely to increase the magnitude and thickness of compaction. High intensity disturbance that results in compaction (e.g., tracked vehicles), is usually expressed at greater depths because the surface soil structures are fractured, low soil depths compressed, and fine textured materials migrate downward to accumulate in areas of horizon or textural transition. Even very sandy soils have some amount of clay bound to sand particle surfaces that upon disturbance become released and then accumulate at lower depths. Accumulation of clays at the compaction horizon further restricts drainage and aeration causing “pan-like” differences that effect physical processes (e.g., soil chemistry, redox potential) and below ground biological activity (e.g., root growth, aerobic microbe activity).

Obviously, higher compaction magnitudes and thicknesses equate to greater influences on soil processes, extended periods for natural attenuation, reduced land management options, and, if remediated, greater expense to recover compacted areas. Depth to compaction influences the type and rates of biological activity as well as the “services” that the soil provides; also, depth of compaction influences the types of plants that can be supported above ground (e.g., deeper rooted species are more impacted by compaction than shallow rooted species). These factors need to be considered when rehabilitating or sustaining managed landscapes and be reflected in developing realistic goals and expectations for future-use and sustained-use conditions. For example, highly compacted areas may not be suited for meeting long term RCW recovery goals, may need more frequent vegetation management (e.g., fertilization, seeding) or be less well suited for repeated military training.

Fine textured soils are inherently more compact because particles can be more densely nested; therefore, small changes in soil density can result in changes in aeriation, chemistry, and water availability; thus, dramatic influences on the biological setting. Other important features that influence the effects of compaction is root density, mineralogy of clays, soil particle structure, and the textural profile. Textural profiles influence compaction because they define “bottlenecks” in drainage. This is particularly true in the sandhill physiographic region because rapidly drained surface sands are often underlain by fine-textured, less-permeable sub-soils and parent material. Several studies indicated that compaction in sandy surfaced soils had greater impacts and were much slower to recover from disturbance. These observations may reflect the fact that either surface sandy soil structures are more friable, hence vulnerable to disturbance or that compaction more greatly alters the influence and interaction with sub-soil processes and resulting conditions.

Besides influencing drainage, soil compaction alters other soil processes directly through its influence on gas and chemical exchange, as well as indirectly by influencing rooting growth and microbial activity; hence, dynamics of decomposition. Chemical influences are important because it defines redox potentials, soil pH, and proportions of anions and cations within soil solution matrix; and with influences on decomposition, nutrient input, output, balance, and availability. Finally, reduced profile moisture holding capacitance and storage results in reduced temporal and spatial storage capacity and greater likelihoods of saturation which forces surface water movement, bulk transport of soil along contour gradients, and sub-surface scouring that results in “rill” or gully erosion. These feactures are magnified by steepened natural or anthropogenic contours or drainage profile gradients.

Compaction tends to be “linearized” because of the generation source (e.g., directional paths, trails, etc.). However, the magnitude can vary due to contour, soil properties, and microsite conditions. Repeated compaction usually reflects a braided land-use that can become self-facilitating as biological activity (root growth, microbes, etc.) is reduced. Further, large compacted areas that have little or no canopy cover and ground cover can be prone to the development of biological and mineralogical crusts that can become a conduit for impeded drainage and accerated runoff. The spatial pattern of crust development and impermeability, due to infrequent use and microsite differences, accentuates the problem because partially permeable locations or linear corridors caused by vehicles tracks become channels for water movement during summer storms, differential absorbance channelizes erosive forces that can then be expressed as gully development. The phenomena of crust development is typically associated with drier biomes that have PET>>precipitation (Coquet 2005), but in heavily disturbed training areas, such conditions do develop and are most likely to occur during the warmest summer months in large areas that receive little or no shade, very limited plant cover, and have little or no organic material in the soil (Coquet 2005).

The loss of canopy results in a series of microclimatic changes, which when permanent, begins to accelerate changes to different stable states. Three principal influences occur: (1) changes in canopy interception, (2) changes in forest floor microclimate, and (3) changes in foliar input. Relative to understory cover, few studies have addressed differences between dense mid-stories and areas without mid-stories (e.g., savannas). It has been determined that grassy areas have very little capacity to intercept and change precipitation input patterns; however, they are important relative to defining the forest floor microclimate and through rapid turnover through out the growing season significantly contribute to foliar input of carbon and nutrients.

A loss or reduction in canopy interception has four principal effects; a) increased precipitation reaching the forest floor (e.g., mature pine stands intercept 22% of precipitation), b) without canopy interference, raindrop energies increase and are more likely to loosen surface soil, c) the loss of interception capacity reduces precipitation lag-rate and increases amplitude of precipitation input (foliage-held water continues to drip after storm events), and d) the loss of continued foliar input reduces nutrient return and results in greater amounts of exposed mineral surface soil. Again, the influence of mid-story has not been determined for most southeastern ecosystems. Differences in rainfall interception by canopy groups was minimal (Reddy 2005); expectedly open pine savanna systems would have lower interception rates simlar to those found by Liu (1998). However, the pine systems have higher-use rates which compensates for reduced interception; thus, watershed yield is likely to be similar between closed forest upland hardwood and hardwood-pine systems and open longleaf pine savanna systems. Again, closed canopy pine systems had the highest interception rates and those with dense mid-stories would be expected to have slightly higher values. Interestingly, the fairly recent change (last 15-20 yrs) in management emphasis toward open longleaf pine savanna systems from closed forest upland pine, pine-hardwood, and hardwood pine systems is likely to have changed within stand water-use patterns. However, any influence is likely to be temporary with the advancement toward to stable uneven aged longleaf pine systems due to increased forest floor cover.

Changes in microclimate, following canopy loss, develop from increased heat energies and air movement, particularly at or near the ground surface. Increased direct sunlight results in elevated surface soil temperatures which accelerates surface soil chemical reactions, dries the surface soil, and facilitates soil crust formation. The development of soil crusts reduces water permeability. Increased soil chemical reaction rates increase decomposition rate and nutrient release. Collectively, surface organic material and form quickly shifts toward increased labile C which with mineralized nutrient forms are quickly lost via surface runoff and rapid perculation of soluabilized and suspended material.

The loss of canopy cover results in changes in foliar input. Foliage is a critical component of regulated nutrient and carbon cycling because it provides a fairly continuous supply of highly decomposable carbon and nutrient sources. A loss or shift in foliage input ultimately effects microbial efficiency due to changes in C:N ratio's as well as indirect influences on surface soil moisture and temperature due to the absence of litter and canopy shade. The loss of foliar input also reduces soil surface moistures, and collectively all of the influences result in reduced local moisture availability between rainfall events. Another impact of lost foliar inputs is likely to be on earth-borne macro-nutrients such as P, K, Ca, Mg, etc.; this would be particularly true in areas with sandy to excessively sandy soils that have limited cation- and anion-exchange capacity. Though N-balance is important, nitrogen availability is often compensated for by increased nitrogen fixation by free-living bacteria (at least seasonally) which is driven by increased temperature regimes, assuming moisture availability is not limiting. Overall, canopy removal is likely to increase the importance of the availability of nutrients other than nitrogen; therefore, other factors (soil moisture, P availability, etc.) become rate limiting and are difficult to detect through simple soil sampling because percentages within the soil may not be available.

The loss of ground surface cover includes the removal of detritus as well as understory and ground cover. Overall, the presence of living and dead plant material reduces impact energies associated with rainfall. The force associated with rain is sufficient to loosen surface soil; thereby, creating “suspendible” mineral soil for erosion. More importantly, the presence of living and dead material on the soil surface interrupts water flow and provides kinetic energy resistence; thereby slowing water movement, accerlerating perculation into the loss or realignment of ground surface cover. Therefore, laminar flow of water is reduced by complex soil surfaces which are facilitated by plant cover and the presence of litter (branches, twigs, leaves, etc.).

Upland forest health and productivity

Long-term sustainability is necessary for Fort Benning to continue to meet necessary training requirements and supporting infrastructure as well as continued advancements toward the recovery of endangered species, compliance with air and water quality standards, and other environmental concerns. Part of this assessment includes acute, compliance-related conditions, as well as chronic effects that influence the implementation. Several integrated issues currently exist and have been prioritized. Each reflects both current- and past-use impacts as well as future expectations. Tree health and growth were negatively affected by training above intermediate levels. The source of declining tree health was not evaluated by these research projects.

Based on Garten’s model (2005), some landscape settings are insufficiently capable of sustainable forestry within the near future due to N-limitation associated with microbial activity and soil carbon storage. This model suggests that frequent burning accelerates the associated burning due to the depletion of carbon reserves and limited carbon input from the existing cover. This finding needs to be further evaluated relative to tree health, growth patterns, and redefinition of existing allometric equations for current soil settings. These findings, with observations of prolonged impacts on soil quality (Maloney et al. 2008) and forecasted impacts of soil quality relationships with burn cycles (Liu 2008), suggest that cumulative “tipping point” of stressors that impact processes involved in defining aggrading, sustaining, or degrading soil and forest productivity.

Soil texture, fire, and training effects were directly evaluated through planting by Collins et al. 2005. The University of Florida group further confirmed this pattern through field observation. Generally, the combined effects of clayey soils, frequent burning, and intermittent training results in reduced survival of planted longleaf pine seedlings. Generally, exposed clay, heavy disturbance, and frequent fire resulted in decreased survival of lomgleaf pine seedlings. Liu et al.(2008), modeling effort also found biennual burn cycles to be potentially detrimental to carbon storage because of direct and indirect impacts on soil cycles.

Consistently, Fort Benning plantings of longleaf pine have marginally satisfactory survival (30-50% after 3 years) on poorly suited sites. This should raise the question as to the appropriateness of these plantings and techniques relative to survivorship elsewhere in the region. However low seedling survival will not affect the long-term objective to develop a low-density, uneven aged longleaf pine dominated woodland and savanna in most areas, but a short-period of unsuitability for RCW may occur during this transition in some stands with early senescence of mature loblolly pine trees. In other areas (e.g., xeric, hydric), the unexpectedly low survirorship suggests that the appropriateness of planting should be questioned on a case by case basis, and not driven by demands to create future RCW habitat.

Heavily used areas have limited potential due to continuous use and past influences. These areas should favor those species that persist such as deeply rooted, sprout-capable scrub-shrub and mixed woodland systems. However, mid-story conditions should be regulated through controlled fire to reduce wildfire risk and maintain ground cover suitability for disturbance dependent sandhill barren and pine savanna species. These areas are well suited to support gopher tortoise and other open habitat species (e.g., bachman's sparrow, henslow's sparrow, oven bird, etc.). Further, patterns of use should take advantage soil holding properties associated with deeply rooted shrubs and small trees (e.g., hawthorns, scrub oaks). Garten 2005, found that heavily disturbed areas had nutrient and carbon relations that were insufficient to support long term achievement and sustainability of longleaf pine systems. However, nutrients and carbon conditions of well-trained scrub/shrub habitats were much closer to forested systems (pine, mixed, hardwood) than to open barren areas.

Relationships between productivity, carbon cycling, and nutrient dynamics

Carbon and nitrogen

Nitrogen dynamics and budgets, associated with soils as well as above- and belowground resources, were estimated by the Prescott College and Univ. of Florida/Purdue groups; and experimentally evaluated by Savannah River Ecology Laboratory and ORNL (Garten) groups. These measures are significant steps toward future understanding and landscape modeling of land management- and military use-impacts on sustainable conditions.

Relative to Carbon stocking levels, Garten (2005) found some differences between vegetation and soil texture. Similarly, Reddy et al. (2005) found differences between vegetation types within different watersheds, these significant differences associated with vegetation, training intensity, and soil texture. The values for soil biomass, C, and N found by the various SEMP investigators are consistent with those from other research studies.

Differences between riparian and upland forests are consistent with other studies (Garten et al. 1977, Christensen et al. 1986, Brinson 1990, Lockaby & Walbridge 1998, and others). Riparian forests serve as C- and nutrient-"sinks," while the relative role of upland forests depends on age, composition, and biomass. With continued growth, forests do store carbon above- and belowground, however, after 14 years of growth no significant gains in soil carbon were observed by Markewicz et al., 2002, other studies have had similar findings. Based on Boring et al. (2005), Hendricks et al. (1998), and findings by others, biomass and litter carbon loss through burning is inconsequential and quickly regained through regrowth of sprouts, germinants, and elevated tree growth. However, some questions still exist as to whether repeated burning of successional pine forests slows the rate of soil carbon accumulation and tree growth (Boyer 2000). Liu et al. (2008) findings support the concept that very frequent burning can be detrimental in actively used forested training lands that are composed of mature successional pine forests.

Table 23. Differences between riparian and upland forests in total soil C and N content.

Total Soil C and N content			Riparian		upland	
			Mean	SE.	Mean	SE.
Organic horizon						
Litter biomass (g/m2)			1308	76	1246	78
Total C (g/m2)			526.0	60.7	573.0	31.8
Total N (g/m2)			10.6	3.4	8.2	4.0
mineral horizon						
POM (g POM/g of soil)			77.2	2.4	84.1	0.8
% soil C in POM			31.7	1.8	40.6	1.4
% soil C in MOM			68.3	1.8	59.4	1.4
mineral horizon						
Soil C stock (g C/m2)		0-10	2821	196	1638	96
		10-20	1612	123	694	43
		20-30	1176	129	415	31
Soil N stock (g C/m2)		0-10	88.4	6.9	50.7	4.2
		10-20	47.1	4.1	21	2.1
		20-30	38.9	6.3	13.7	1.7

Exchangable forms of N are regulated by microbial activity, atmospheric input, organic cycling, and storage capacity. Beyond the expressed values of available forms below (NO_3, NH_4), annual N-fixation, nitrification, and mineralization rates are also given. As identified by Collins et al. (2005), these values vary with soil texture; generally, clayey soils have higher levels of N, and other nutrients, as well as greater exchangeable concentrations. As found by Garten (2005), Kryszik (2005), and Collins et al. (2005), military training results in a temporary increase in availability but when microbial activity is effected, a decline in availability and influx results. Like soil compaction, stabilization of these processes and conditions may take many years, particularly on clayey soils. Hence, productivity expectations for heavily disturbed sites may be limited for decades (Garten and Ashwood, 2004b).

Like Total N, exchangeable forms of N are also higher in the riparian zones (Table 24). Nitrate levels are more comparable between the two settings, but these levels are likely to be inconsequential to total N budgets because of high mobility and loss. Reaction rates such as mineralization, nitrification, and Net N production are also higher in the riparian areas, presumably because of moisture regimes that allow for near-continuous microbial activity and slightly lower C:N ratios. N-demand is also likely to be much higher in the riparian areas due to higher plant biomass and higher growth rates. Therefore, though more available, N may be more tightly conserved in these systems. A critical aspect to management is to maintain the riparian forest in a "sink" condition that conserves nutrients (NO_3^-,PO_4^{3-},K^+) that would be harmful to stream ecosystems, and stores soil carbon reserves. The greatest threat to the performance of these "ecosystem services" is bulk transport of materials through erosion and overburdening inputs from the neighboring terrestrial landscape. Based on Maloney et al. (2006), phosphate and nitrate levels are elevated in streams with high percentages (>14%) of exposed soil within the watershed. This may indicate that the chemical conservation effectiveness of the riparian system may be at or near its input and storage capacity.

Table 24. Differences between riparian and upland forests in N reaction rates and mobile N-forms.

N reaction rates and mobile N-forms			Riparian		Upland	
			Mean	SE	Mean	SE
Extractable NH4-N		ug/g of soil	3.8	0.5	1.7	0.3
Extractable NO3-N		ug/g of soil	0.127	0.061	0.103	0.042
soil N mineralization		ug/g of soil	14.6	5.2	6.0	2.4
Net nitrification		ug/g of soil	11.2	4.9	8.1	3.3
Net N production		ug/g of soil	3.9	0.4	1.1	0.6

Relative to burning, the relationships found by Garten (2005) and (Collins 2005, LaJeunesse et al. 2006) suggest that burning more frequently than 3 years results in an accrued N deficit that ultimately will deplete soil quality and productivity. They contend that N-fixation associated with legumes is insufficient to meet losses associated with volatilization and soil transfer. These findings were inconsistent with other research findings (Hendricks and Boring 1992, 1999, Hainds et al. 1999, Hiers et al. 2003, Boring et al. 2005), which acknowledge the potential for short-term deficits but have found that post-fire N-fixation by legumes, quickly restore N-losses in areas with 3 year dormant season return frequencies. LaJeunesse et al. (2006) found values and response comparable to Piedmont sites described by Hendricks and Boring, 1999.

These differences in findings at Fort Benning were consistent with those by Garten and Ashwood (2004), and may be attributed to: (1) low initial legume density and response to fire, (2) low legume activity rates relative to other locations, (3) strong legume relationships with soil texture influenced moisture availability and canopy openness, and (4) site history (training, burning, silviculture). Hidden influences that may also explain these findings include long-term influences of soil compaction associated with military land-use that may result in chronic restrictions of legume seed availability (low density, low establishment, seed dispersal limitations) or phosphorus availability limitations. Because of the projected consequences (Garten and Ashwood, 2004b) of interactions between soil, burn frequency, and military-use; continued investigations to resolve this relationship are needed. These studies should include longer term evaluations that include non-drought years with different fuels and fire behaviors as well as involve different areas, soil settings, and canopy types. Potentially, pine forests established on burdened agricultural lands within the sandhill province may not have the same N-cycling relationships as established longleaf pine systems elsewhere in the Coastal Plain province; in fact, the dynamics within these successional forests, independent of canopy type, may be more closely tied with lower Piedmont systems.

Other earth-borne elements

Other mineral soil nutrients were evaluated by SEMP research associated with the Univ. of Florida & Purdue Univ. projects (Reddy, 2005). Though not emphasized by SEMP studies, nutrient balance and the availability of other major nutrients (e.g., P, K) are known to be limiting features under harsh conditions or industrial forest areas. Generally, most of the upland areas samples had moderate levels of training disturbance, whereas, most of the lowlands and riparian areas had low disturbance or indirect disturbance (erosion). A significant interaction effect was also noted between watershed and disturbance condition. Therefore, this implies that each watershed should be uniquely considered when predicting or projecting nutrient loading responses to additional or lessed military training. These patterns are also likely to be expressed when assessing expected vegetation impacts and change. Again, the likely covariate (or regulating feature) associated with these patterns is soil texture, condition, and quality.

For all mineral soil concentrations analyzed, the riparian areas had significantly higher concentrations of exchangeable concentrations. Though most elements weren't analyzed for total nutrient content, cations and phosphorus are typically at much larger levels in finely textured riparian soils; therefore, the differences between upland and riparian sites would be magnified.

As evidenced by the standard deviations associated with the riparian and upland averages (Table 25) a great deal of variance existed between watersheds (Reddy, 2005). Similarly, high levels of variance existed within each watershed (Reddy, 2005). Overall, at both the riparian and upland sites, low disturbance conditions resulted in higher levels of exchangeable and total nutrients. Consistent with Kryszik's findings (2005), the greatest difference was between the moderate and several disturbance sites.

Relative to other studies in the lower Coastal Plain, the exchangeable concentrations of nutrients at Fort Benning are relatively low. This is likely to be an artifact of physiographic province and soil origin as opposed to military training impacts. It has long been recognized that because of high concentrations of coarse, quartzite-derived sands within the rooting profile, soil of the sandhill physiographic region are generally less productive and have lower nutrient reserves when compared to other locales (Wells & Shunk 1931). Though macro-nutrients are in lower concentrations and total amounts, the SEMP observed nutrient proportions and ratios are consistent with other locations within the southeast for upland and stream bottomlands.

Table 25. Differences between riparian and upland forests in total and exchageable nutrient levels.

Total & Exchageable nutrient levels			Riparian		Upland	
			Average	Std	Average	std
Disturbance		Low	0.78		0.26	
frequency		Mod.	0.18		0.60	
		Severe	0.04		0.14	
exchangeable	Ca	mg/kg	207.7	162.7	161.3	144.8
	Fe	mg/kg	223.3	218.8	33.7	16.0
	Al	mg/kg	478.8	380.2	240.0	89.3
	K	mg/kg	38.7	19.8	29.3	18.5
	C	mg/kg	74.3	38.7	62.0	29.7
Total	C	mg/kg	24266.7	16333.3	10213.0	4233.3
	N	mg/kg	1343.2	895.2	393.4	153.3
	P	mg/kg	166.3	95.3	74.8	31.2

Garten (2005) and Collins (2005) found mineral soil C:N ratios highest in upland sites, particularly sandy soils. Both studies found, with disturbance, C:N ratios declined in areas with sandy soils, but increased slightly on clayey sites. Finally, pine forests had the highest C:N ratios and deciduous forest and scrub communities had the lowest ratios.

Landscape pattern, complexity, and connectivity

Based on satellite imagery, aerial photography, and other GIS resources; landscape heterogeneity has increased since settlement, particularly during the past 30+ years. The increase in complexity, and loss of connectivity, is partially due to differential land-use expectations, application of greater amounts of land area to human needs, and compounding residual affects associated with historic (19th century activities) and more recent (20th century, pre- and post-“Camp” Benning) land-use. Prior to European settlement, native Americans used bottomland and some adjacent upland areas along the Chatahoochee for agriculture; much of the uplands served as game preserves for hunting and gathering of native foods. These areas were periodically burnt to improve productivity of food (berries, etc.) and browse for game, reduce native pests (ticks, etc.), and generate more open conditions for hunting.

Since European settlement, much of the once-governing longleaf pine and mixed pine-hardwood ecosystems were converted to large tracts of agriculture; poorer soils used for animal husbandry, better soils used for row crop and sustainance farming. It’s also likely that some residual woodlots were retained as a source of firewood and free-range cattle and hog farming. Further, the poorest soils were more likely to have been abandoned from agriculture early on during the settlement period. The presence of free range cattle and hogs as well as fire protection in the remaining woodlots (mostly associated with stream corridors) is likely to have severely impacted native grasses and forbs as well as tree seed (e.g., acorns) and seedlings.

However, the conversion from expansive longleaf pine ecosystems to expansive agriculture is not likely to have significantly changed the pattern of spatial frequency and proportion, simply the ecosystems (forest vs. open agriculture) associated with each group. In a sense, “islands” of open successional areas became the landscape, as the landscape of mature longleaf systems became “islands”; all remained partially connected to stream corridor systems that transitioned from hydrology and fire-influenced to altered-hydrology, selective-harvest influenced riparian systems. The remaining landscape essentially consisted of scattered islands of poor soils (e.g., xeric sandhills), a few isolated woodlots and rural home-sites, and narrowly treed margins along larger streams that led to a post-native American agriculture mature forest river margin along the Chatahoochee River.

Upon abandonment of agriculture (late 19th century/very early 20th century) began to proceed toward early successional systems. With differential sorting of species, successional processes advanced toward young forest ecosystems but was strongly influenced by residual sprouts, buried seed pools, seed-source proximity and movement, and site productivity. In some areas of pre-WWII “Camp” Benning, the successional process became interrupted by active military residence, training, and resource-use (e.g., tree harvest for construction, grazing by cavalry horses, dismounted soldier maneuvers, bivouac, etc.). With the onset of WWII, land area was added to Fort Benning and troup training involved greater use of mechanized equipment. The additional land added to Fort Benning, was more forested through tree planting and successional advancement. For safety reasons, the increased use of mechanized equipment (e.g., tanks, artillery, advanced munitions, etc.) began to “compartmentize” specific training events to localized areas, which led to localized differential effects and greater spatial complexity on the landscape. During the mid-20th century, economic disparity during the 1930’s and agricultural advances, led to an off-post rural landscape that included a wider variety of land-use types on smaller tracts of land. Urbanization also led to greater higher human population densities as well as greater patchiness and variety of land-use. Finally, land ownership patterns during the latter 20th century have continued to change away from subsistence agriculture toward corporate land ownerships, most notably the forest products industry, and urban interface populations.

Land-use on Fort Benning following WWII also changed as the U.S. Army became restructured and military installations became task-specialized (e.g., Fort Benning, Home of the Infantry). During the post WWII period, land-use for training increased and become more specialized; thus, leading to local areas specific to certain tasks. This coupled with continued succession, forest-use, and specialized training requirements has led to advancing complexity and patchiness on the landscape. Further, past land-use and site quality has reduced land-use flexibility and management opportunities in some areas (e.g., severely eroded areas, cantonment areas, DUD areas, etc.). These observations are consistent with analysis by Dale (2006), whereby landscape complexity and “graininess” has increased during the past30-40 years. Further, the frequency of compatible adjacent habitat polygons has declined resulting in greater perimeter:area ratio with higher boundary frequencies. Overall, the proportion and evenness of polygon types has significantly changed since historic conditions of the 1800’s as well as those from the early 1900’s. This implies that a more complex pattern and mosaic of habitat units now exists, the relative frequency and proportion has changed, and the average polygon size has changed. Thus, a greater likelihood of temporary or permanent barriers is now present, and continuing to increase.

Today, current demands and residual land-use artifacts continue to influence training flexibility and opportunity, and with continued change in military trainings may potentially future limit future military training opportunities and compliance expectations. The consequences of a more dissected landscape is a greater likelihood of restricted ecological connectivity, reduced effectiveness of inherent- and management derived regulating processes (e.g., controlled burning) toward optimal sustainability, and greater cost associated with meeting a complex set of landscape goals (e.g., advanced military training, TE recovery, soil stabilization, water quality, sustainable and renewable forestry, etc.). Changes in the surrounding landscape also influence the progress and regional importance of these landscape goals. Relative to the surrounding landscape, a depleted off-post landscape equates into an advanced responsibility of Fort Benning to meet and exceed their expected compliance responsibilities.

Various landscape level features can be evaluated using remote imagery information and are critical in assessing local and landscape processes (Turner 2005). Consistent with many other studies, those the attributes identified by Dale (2006) are reflective of current conditions and future-use scenarios. Generally, connectivity between like habitats have declined during the 20th century with unknown impacts. The most important features include the proportion of landscape cover types, the shape and distribution of these landscape cover types, and the constancy and variation within. The proportion of landscape cover types defines habitat patterning, watershed features, and future-use alternatives. The shape and distribution of these features further defines species-specific occurrence and suitability relative to size, shape, and connectivity (Turner 2005). Patterning and transition within and between land cover types further define within system processes (Wagner & Fortin 2005). The importance of system- and species-specific connectivity has been evaluated for various abiotic and biotic systems. Undoubtedly, patterning and connectivity contributes to long-term sustainability and functioning.

The role of plant lifeforms to site stability and sustainable conditions

A series of species and lifeforms were identified as being responsive to various forms of training stress with and without the combined influence of land management. In all cases, ecological condition (recent history, moisture setting, soil conditions) governed responsiveness to disturbance as well as the trajectory of post-disturbance recovery. Specifically, because of sensitivity to specific aspects of disturbance some conditions favor some life forms. These findings are consistent with other studies (Laessle 1958, Christy & McGinty 1977) as well as the original observations of life forms (Daubenmire 1946). For example, compacted soils are generally poorly suited for bulb-derived species (geophytes); assuming sufficient viable seed is available exposed, loosened soils favor annuals (therophytes); finally, shrubs and woody species (phanerophytes) are strongly impacted by disruptive surface disturbances.

Not unexpectedly, frequent and intense disturbance favored annual species establishment. Less frequent disturbance favored hemicrytophytes (mostly Asteraceae & Poaceae); and disturbed areas allowed to recover favored a variety of early successional perennial forbs, grasses, and soft mast species of the Roseaceae (particularly *Rubus* and *Prunus* species). In most areas, the continued absence of disturbance results in the eventual reestablishment of additional crytophyte, geophyte, and phanerophyte species as well as longer lived hemicryptophytes. The rate of reestablishment as well as species types is highly dependent upon the post-disturbance suitability to support a suite of species, previous biotic settings and their contributions to a residual seed bank, species dispersion patterns, and successional inertia. Finally, low level disturbances (e.g., dismounted training) as well as periodic burning allows for some persistence of annual species in disrupted areas.

Intermediate or infrequent disturbance tends to have similar effects to intense disturbance but persisting species reflect multiple lifeforms. Compaction greatly impacts the persistence of geophytes and species with significant resources stored beneath the soil surface. Vines, woody and non-woody species, tend to rapidly expand with canopy loss in localized areas. These vine species and resprouting scrubs and small saplings greatly influence the vertical distribution of biomass and fire behavior response. Often these resprouting vines and shrubs are interrupted by linear corridors (e.g., paths) of bare ground, therefore, fire movement and expressed energies are interrupted by breaks and changes in fuel type and amount. Cool season fires associated with grassy ground covers typically are incapable of igniting moisture-rich mid-story fuels. In constrast, warm-season fires under dry conditions in these same areas may result in escaped or crown fires.

Intermittent training-use may also deplete species richness and biodiversity (Grime 1985). However, these effects are likely to have occurred during periods of past-training use. Several species are known to occur elsewhere in the surrounding counties but have very limited presence or are undocumented. This may indicate that these species were eradicated during a much earlier time period.

Impacts of military land-use on species diversity, composition, and biological function

Disturbances are poorly-adaptable disruptive forces that result in changed health of individuals, species suitability, and ecological function. These changing conditions can lead to losses of individuals and species, compositional shifts, changes in species diversity patterns, and the loss of habitat quality as well as the efficiency, placement, and proportion of landscape level ecological matrices. Even system specific maintenance components such as periodic burning can result in observable change; in fact, when controlled these changes are expected to facilitate further advancement toward historic conditions and desired states. As “place holder” alliances and associations, The Nature Conservancy has identified a series of target conditions that could be used used as restoration targets.

Anthropogenic disturbance, those created by humans, can have differential effects that may or may not be consistent with natural regimes and responses. Further, it’s unknown as to the residual effects of long term use or the responsiveness of these expectedly adapted systems to further perturbation. An observed pattern is that most literature-cited diagnostic species have very limited occurrence on the Fort Benning landscape; however, similar patterns exist in nearby locations, therefore, the absence of these species may reflect earlier land-use (e.g., 19^{th} century agriculture). What remains to be evaluated is whether initial training eliminates some species allowing other better suited species to persist or whether training in past-use areas has the same effects on plant communities as in initial-use areas. Further, some advancement on this issue could be made by comparing diversity patterns in areas that have been abandoned from training as well as comparisons of vegetation in areas that have never been used for military training (e.g., small cemetery areas that have remained burned by controlled or escaped fires).

SEMP studies have collectively identified a series of species that are reflective of soil and forest settings but responsive to different levels of training disturbance and combined impacts with forest management activities. For the most part, these species and associated patterns are consistent with other regional successional studies and disturbance regimes. In general, species richness declines with increasing training; further, the species present tend to be annuals and disturbance tolerant species such as those associated with harsh, unproductive sandhill barrens. Collins (2005) found that heavily disturbed clay soil sites have much higher abundances of xeric associated species. This is suprising because these species are typically associated with xeric, unproductive sites not heavily-impacted, clayey soil sites. This suggests that many species associated with sandhill barrens are prolific through persistence & avoidance mechanisms, not competitive exclusion & tolerance (typical of upland hardwood ground covers) or effective post-disturbance dispersion & establishment (typical of pine savanna ground covers). In ordinational space these heavily impacted, clayey soil sites also had vegetation assemblages comparable to those found in sandhill barren areas (Collins et al. 2006).

After further standardization, we recommend that the species-sensitivity rankings for the following vegetation groups be applied as weighted indices in compositional analysis, much like those used for vegetation as part of the wetland delination protocols. Using weighted analysis would allow for tracking compositional change with reduced emphasis on individual species. Two conditional targets could be created; managed species targets associated with open ranges (e.g., Bermuda grass) and diagnostic indicators of natural reference communities. For very different purposes, both could be used as a compass toward vegetation stability associated with training and progress of management actions. In the former case, loss of maintained plant cover and replacement by early successional species would indicate a need to reduce training impacts or replanting. In the latter case, reference species and those associated with higher quality conditions could be used to monitor management progress as well as degradation associated with infrequent training. Fire-dependent species could also be used to evaluate the efficiency and effectiveness of prescribed fire programs. With continued monitoring, species indices could be adjusted to represent improved relationships with disturbance and topo-edaphic relationships (soil texture, topography, hydrology, etc.).

In conjunction with these measures of composition, other measurements such as invasive species occurrence, structural diversity, and metrics of species richness and diversity, such as using outlined by NRC (2000), should be used to further evaluate change and pattern of habitat type and quality for other components of the ecosystem (e.g., fauna).

Table 26 summarizes the responsiveness of understory woody species (including seedlings, saplings, etc.) to military training (l = light, h = heavy, int = intermediate), the number of plus signs indicate significance level (+ = $p<0.05$, ++ = $p<0.01$, +++ = $p<0.005$). Because these evaluations involve multiple studies, significance is represented by a “mid-point” value of significance associated with the various studies. Caveats for interpretation of these tables include, all research groups evaluated “light” and “heavy” disturbances differently, and these relationships were based on existing site conditions not experimental evaluations. Therefore, the relationships represent cumulative impacts of training, not the impact of specific training sequences between t and t+1 time periods. Further, imbedded within these sites, and data, are unaccounted legacy impacts. Listed species are those either collectively identified by SEMP researchers or those identified by multivariate species indicator analysis (Dufrene & Legendre, 1997) using presence-absence data from all studies, excluding CS-1114A first phase and CS-1114B second phase data sets.

In contrast, experimental set-ups to consider pre- and post-response to a particular treatment generally have insufficient time frames to fully account for compositional change. For example, controlled burning and silvicultural treatments often have short-term influences that are often inconsistent with long-term change. The left most column lists other factors that were found to have significant associations with each species. These include fire frequency response (Collins), soil texture (Collins), successional age (U. of Florida), and canopy type (Collins). In a sense, these would be covariates to the expected response and occurrence in military training areas.

As indicated by Dale’s analyses of life forms, most woodly species are strongly affected ($p < 0.01$) by miltary training. This is particularly true for woody species associated with hardwood systems; red maple (*Acer rubrum*), white ash *(Fraxinus americana)* ,tulip poplar *(Liriodendron tulipifera)*, white oak *(Quercus alba)*, American elm *(Ulmus americana*), dwarf live oak (*Quercus minima*), Shummard oak (*Quercus shummardii*), spruce pine (*Pinus glabra*), red buckeye *(Aesculus pavia),* red bud *(Cercis Canadensis),* paw paw (*Asimina parviflora*), beautyberry (*Callicarpa americana*), swamp huckleberry (*Gaylussacia frondosa*). Simlarly, several woody hardwood species were significantly associated with infrequent fire; this finding is generally consistent with the purpose of burning (frequent burning to reduce understory hardwoods). Relative to this grouping, many important hardwoods are not listed, and include American beech (*Fagus grandifolia*), southern magnolia (*Magnolia grandiflora*), black oak (*Quercus velutina*), scarlet oak (*Quercus coccinea*), chestnut oak (*Quercus prinus*), Arkansas oak (*Quercus arkansania*), swamp chestnut oak (*Quercus michauxii*), cherrybark oak (*Quercus pagodifolia*), northern red oak (*Quercus rubra*), southern sugar maple (*Acer barbatum*), chalk maple (*Acer leucoderme*), American basswood (*Tilia americana*), and some undifferentiated hickories (*Carya cordiformis, C. glabra, C. ovata, C. ovalis*) as well as various other shrubs and trees associated with slopes and bottomlands. These species should be considered as strongly to moderately intolerant of military training; thus, their loss is an indicator of habitat degradation on suitable landscapes (loamy to clayey slopes, transitions, and bottomlands).

Woody species that increase in proportion with burning include several shrubs and mid-story groups, such soft-mast species include plums (*Prunus* spp.), hawthorns (*Crataegus flava, Crateagus spp*., except *C. sphaerocarpum*), persimmon (*Diospyros virginiana*), American holly (*Ilex opaca*), georgia hackberry (*Celtis tenuifolia*), black cherry (*Prunus serotina*), blackberry (*Rubus cuneformis*), creeping dewberry (*Rubus trivalis*), poison ivy (*Toxidendron radicans*), and greenbriers (*Smilax bona-nox, Smilax glauca*). Most oaks had negative associations with training intensity, except two scrub oak species (*Quercus margaretta, Quercus incana*). An aggressive non-native vine (*Lonicera sempervirens*) was also positively associated with disturbance intensity.

These findings indicate that even heavily disturbed areas that have broken canopies continue to provide soft mast and some hard mast to wildlife. Though these observations are inconsistent with the general management target of an upland pine matrix, these areas do provide wildlife habitat and should deserve special consideration for resource planning. During training and military-use some vegetation patches are avoided. These areas should be “managed” to optimize habitat value and minimize erosion potential. The greatest risk to alternative habitat-uses is increased establishment and expansion of invasive species. These areas could also be supplemented with some coordination to protect trees and patches of a particular size. In many cases, these areas also harbor infrequently occurring species; though a population "sink" these areas provide some connectivity with better established and protected populations. Most mid-successional tree species such as sweetgum (*Liquidambar styraciflua*), loblolly pine (*Pinus taeda*), water oak (*Quercus nigra*), sand laurel oak (*Quercus hemisphaerica*), southern red oak (*Quercus falcata*), hickory (*Carya spp.*), and winged elm (*Ulmus alata*) were associated with intermediate or less strongly associated ($p < 0.05$) light training. Simlarly, successional shrubs and vines like winged sumac (*Rhus coppalina*), *Sassafras albinum*, wax myrtle (*Myrica cerifera*), trumpet creeper (*Campsis radicans*), Virginia creeper (*Parthenocissus quinquefolia*), grape (*Vitis rotundifolia*), and *Smilax rotundifolia* had weaker associations with light training intensity. Again, these areas provide some habitat for successional species (a designated habitat recovery target by Partners In Flight, 2005). Areas dominated by these species are also tolerant of infrequent heavy disturbance or repeated light disturbance, and these species protect watersheds against degradation; therefore, in disturbance "sensitive" watersheds should be valued. Not surprisingly, most fire associated species like longleaf pine (*Pinus palustrus*), shortleaf pine (*Pinus echinata*), blackjack oak (*Quercus marilandica*), turkey oak (*Quercus laevis*), and post oak (*Quercus stellata*) had weak associations with disturbance. Fire tolerant shrubs associated with mesic and wet fire communities also had weak associations with disturbance, some of these species include titi (*Cyrilla racemosa*), little gallberry (*Ilex glabra*), and poison sumac (*Toxidendron vernix*). However, shrubs associated with these upland systems were strongly associated with light training, these include dwarf huckleberry (*Gaylussacia dumosa*), and blueberries such as sparkleberry (*Vaccinium arboretum*), *Vaccinium myrsinites*, and deerberry (*Vaccinium stamineum*).

The difference in upland tree and upland shrub relationships with disturbance intensity may reflect spatial scale and pattern of military-use, while differences with lowland shrubs may reflect adaptability to disturbance associated with fire intensity. Whereby, lowland fire-maintained shrubs are adapted to higher fire intensities (higher soil disturbance) through more effective sprouting adaptations to reacquire released resources. Further, lowland shrub communities associated with pine canopies tend to have higher densities, thus, a greater likelihood of recovery. Because the understory woody component is a critical issue in evaluating progress toward meeting RCW habitat requirements, expected shrub densities and compositions should be used as indicators relative to soil and landscape position.

Based on this information, the best woody species indicator of upland pine forest disturbance are the abundance of *Gaylussacia dumosa* and *Vaccinium myrsinites*. Both are very low lying shrubs that are capable of sprouting but are generally poor at establishment (Kwit & Platt, 2005).

Table 26. Upland tree and upland shrub relationships with disturbance intensity.

Groundstory Woody Species	Training	Other Significant Relationships
Acer rubrum	l ++	Moist, infrequent fire, mature, other
Aesculus pavia	l ++	Moist, clayey, infrequent fire
Asimina parviflora	l ++	Moist, sandy
Callicarpa americana	l ++	Moist, loamy
Campsis radicans	l +	Loamy, successional
Carya sp.	Int	Sandy
Celtis tenuifolia	h +	Sandy
Cercis canadensis	l +++	Moist, clayey, mature, other forest
Corylus americana	l +	Moist, loamy, mature, other forest
Crataegus flava	h ++	dry, sandy
Crataegus sp.	h +	Loamy, successional
Crataegus spathulata	l +++	
Cyrilla racemiflora	l +	Moist, sandy
Diospyros virginiana	h ++	Young forest
Fraxinus americana	l ++	Moist, loamy
Gaylussacia frondosa	l +++	Moist
Gaylussacia dumosa	l ++	Sandy, mature, longleaf
Ilex glabra	l +	Moist, sandy
Ilex opaca	h +	Moist, sandy, infrequent fire, other forest
Ilex verticillata		Moist, sandy, mature forest
Liquidambar styraciflua	l +	Sandy, infrequent fire, young forest
Liriodendron tulipifera	l ++	Moist, loamy
Lonicera sempervirens	h +	Successional
Myrica cerifera	l +	Moist, young forest, other forest
Parthenocissus quinquefolia	l +	Sandy, infrequent fire, young forest
Pinus echinata	l +	
Pinus glabra	l ++	Moist, sandy, other forest
Pinus palustris	l +	Sandy, longleaf
Pinus taeda	l +	Loamy, young forest

Groundstory Woody Species	Training	Other Significant Relationships
Prunus serotina	I +	infrequent fire, young forest
Prunus sp. (plum)	h ++	Successional
Quercus alba	I ++	Moist, loamy, mature, other forest
Quercus falcata	I +	Sandy, infrequent, young, other forest
Quercus incana	H +	dry, sandy
Quercus laevis	I +	dry, sandy
Quercus hemisphaerica	I +	Sandy, young forest
Quercus margaretta	H +	dry, sandy
Quercus marilandica	I ++	dry, loamy, frequent fire, mature, LLP
Quercus minima	I ++	other forest
Quercus nigra	I +	Sandy, infrequent fire, young forest
Quercus shumardii	I ++	Moist, loamy
Quercus stellata	I ++	dry, loamy, mature, longleaf
Rhus aromatica	I +	Moist, loamy
Rhus copallina	h +	frequent fire, successional
Toxidendron quercifolia	I +	Successional
Toxidendron radicans	H ++	Moist, young forest
Toxidendron vernix	I +	Moist, sandy
Rubus argutus	I +	infrequent fire, young forest
Rubus cuneiformis	H +	Loamy, successional
Rubus trivialis	H +	Successional
Sassafras albidum	I +	Sandy, young forest
Smilax bona-nox	H +	Young forest
Smilax rotundifolia	Int	infrequent fire
Symplocos tinctoria	I +	Moist, sandy
Ulmus alata	I +	Loamy
Ulmus americana	I ++	Moist, loamy, mature, other forest
Vaccinium arboretum	I ++	infrequent fire, young forest
Vaccinium elliottii	I ++	Moist, mature forest
Vaccinium myrsinites	I ++	dry, sandy, mature, longleaf
Vaccinium stamineum	I ++	Sandy, infrequent fire, mature forest
Vitis rotundifolia	I +	Sandy, infrequent fire, successional

Some composition of woody shrubs should be desired to meet the needs of resident and migratory songbirds. Though most are canopy nesting, insectivores many other associated birds require soft mast and hardmast for feeding as well as ground nesting sites. Overwintering birds require starch- and oil-rich persistent fruits such as hollies, wax myrtle, and hawthorn.

Also, these data suggest that the upland pine matrix ecosystem has a canopy well-suited for light to intermediate disturbance. But, these findings do not address patterns of understory spatial distributions that facilitate fire movement, resource cycling, or understory diversity. Observations associated with herbaceous species are described below. Continued research is needed to evaluate fuel patterning that best facilitates local diversity as well as fire movement that achieves the desired, long-lasting effects toward an uneven aged pine ecosystem.

Like most forbs on the landscape, several indicators of high quality pine savanna diversity are absent or so limited that they were not indicative of treatment response. From moist to dry conditions these species include; *Ageratina altissima, Boltonia diffusa, Brickellia cordifolia,Brickellia eupatorioides, Carduus repandus, Chrysogonum virginianum, Chrysoma pauciflosculosa, Echinacea pallida, Eupatorium fistulosum, Eupatorium perfoliatum, Helenium spp., Helianthus spp., Hymenopappus scabiosaeus, Liatris aspera, Liatris squarrosa, Marshallia obovata, Pityopsis aspera, Rudbeckia hirta, Solidago auriculata, Solidago tortifolia, Symphyotrichum dumosum,* and *Verbesina spp.*. Overall, this listing includes atleast 30 typically aster family associates with an unknown response to military training. Each of these species has a different landscape sere, nearly all are associated with mature longleaf pine or mixed longleaf forests and are positively associated with fire.

Table 27. Forbs relationships with disturbance intensity.

Asteraceae forbs	training	Other significant relationships
Ageratina aromatica	L ++	Moist, mature
Ambrosia artemisiifolia	h +	frequent fire, early successional
Aster concolor	L +++	Successional
Aster dumosus	L ++	Young forest
Aster linariifolius		Loamy, frequent fire, mature
Aster paternus	intermed	Moist, clayey, mature
Aster tortifolius	L +	Young forest
Cacalia lanceolata	L +++	Moist
Cacalia muhlenbergii	L +++	Moist, loamy
Chrysopsis gossypina	h +	dry, sandy, frequent fire
Chrysopsis mariana	Intermed	Loamy, frequent fire
Conyza canadensis	h ++	early successional
Coreopsis lanceolata	l +	Moist
Coreopsis major	h +	clayey, young forest

Asteraceae forbs	training	Other significant relationships
Elephantopus elatus		Moist, early successional
Elephantopus tomentosus	l +++	Clayey
Erigeron strigosus	h +++	
Eryngium yuccifolium	h ++	dry, clayey
Eupatorium album	l +	
Eupatorium aromaticum	l ++	Clayey
Eupatorium capillifolium	Intermed	Loamy, mid successional
Eupatorium coelestinum	l +++	
Eupatorium hyssopifolium	l +	frequent fire
Eupatorium mohrii		early successional
Eupatorium rotundifolium		clayey, frequent fire, mid successional
Gnaphalium helleri		mid successional
Gnaphalium obtusifolium		early successional
Happlopappus divaricatus	h +	early successional
Helianthus floridanus		mid successional
Helianthus longifolius	Intermed	frequent fire
Heterotheca subaxillaris	h +	dry, successional
Hieracium gronovii	l +	Moist, young forest
Hieracium venosum	h ++	frequent fire
Liatris elegans	l ++	dry, mid successional
Liatris graminifolia	l ++	dry, longleaf
Liatris tenuifolia	l +	Successional
Pityopsis graminifolia	l+	Frequent fire, young forest
Rudbeckia fulgida	h +	Mature
Senecio sp.	l +	frequent fire
Sericocarpus asteroides		Young forest
Silphium compositum	l +	dry, frequent fire, longleaf, mature
Silphium dentatum	h ++	frequent fire
Solidago fistulosa		mature forest
Solidago latissimifolia		Moist, mature
Solidago leavenworthii	h +	early successional
Solidago nemoralis		Sandy, young forest
Solidago odora	L ++	Loamy, mature
Solidago stricta	l ++	
Solidago tenuifolia	l ++	Mature

Asteraceae forbs	training	Other significant relationships
Vernonia angustifolia	l ++	dry, frequent fire

Of those species listed below, early successional annuals such as fleabane (*Erigeron stigosus*), horseweed (*Conyza Canadensis),* ragweed *(Ambrosia artemisifolia*), and *Happlopappus divaricatus* were positively associated with heavy military training. Perennials associated with open forests and meadows such as *Coreopsis major, Chrysopsis mariana, Eryngium yucci-folium, Hieracium venosum, Heterotheca subaxillaris, Rudbeckia fulgida, Silphium dentatum,* and *Solidago leavenworthii* also had higher compositional percentages and frequencies in the heavy trained military areas. Overall, diversity of and cover by aster family members were lower in heavily trained areas.
Other species that were associated with intermediate conditions included old field species such as *Aster paternus, Chrysopsis mariana, Eupatorium capillifolium* (yankee weed), and *Helianthus longifolius* (sunflower). The decline of these species and relative increases of the former listed of species (particularly the annuals) should be used to monitor training impacts on open field conditions.

Most mature pine savanna species were strongly associated with light training. These included Veronia angustifolia, Solidago odora, Solidago tenuifolia, Silphium compositum, Liatris elegans, Liatris graminifolia, Eupatorium hyssopifolium, Eupatorium coelestinum, Eupatorium aromaticum, Elephantopus tomentosus, Cacalia spp., Aster concolor, Aster tortifolius, and Aster dumosus, and Ageratina aromatica. The latter species should be used to assess training impacts on existing pine landscapes.

Several diagnostic grasses were absent from the data set or had limited occurrence. For example, several traditional savanna grass associates are absent, these include;*Amphicarpa muehlenbergianum, Anthaenantia villosa, Aristida curtisii, Aristida lanosa, Danthonia spp., Eragrostis elliottii, Eragrostis spectabilis, Gymnopogon brevifolius, Muehlenbergia capillaris, Paspalum praecox, Poa chapmanii, Piptochaetium avenaceum, Sorphastrum elliottii, Sorgastrum secundum*, and *Sporobolus junceus*. For the most part, these species are absent or very limited across the Fort Benning landscape. However, most grasses associated with mature pine savannas are represented in the data set below. Again, from these data, and other monitoring and research efforts, it's difficult to ascertain whether these species are absent due to current land-use patterns, dispersal limitations, or past land-use histories.

Table 25. Grasses relationships with disturbance intensity.

Grasses	Training	Other significant relationships
Andropogon gerardii	l +	Moist, clayey, successional
Andropogon scoparius	int	Young forest, frequent fire
Andropogon ternarius	L ++	Mature
Andropogon virginicus	h ++	successional, frequent fire
Aristida oligantha	int	
Aristida purpurascens	l +	Sandy
Aristida longespica.	L +	Young forest
Arundinaria gigantea	L ++	Moist
Cenchrus longispinus	h +	Sandy, early successional
Chasmanthium sessiliflorum	L +++	Moist, clayey, other forest
Cynodon dactylon	h +	Successional
Dichanthelium aciculare	int	
Dichanthelium anceps		Mature
Dichanthelium oligosanthes	L +	
Dichanthelium rigidulum		Mature
Dichanthelium sabulorum	L +	
Dichanthelium sp.		clayey, successional
Dichanthelium verrucosum		Mature
Digitaria cognata		Successional
Digitaria filiformis	h +	Early successional, frequent fire
Digitaria violascens	h ++	
Eragrostis capillaries	h +	Sandy, early successional, other forest
Eragrostis curvula	h +	
Eragrostis hirsute		Successional
Eragrostis refracta	h ++	
Erianthus contortus	L +	
Gymnopogon ambiguous	L ++	clayey, mature, longleaf
Muhlenbergia expansa	L +++	
Panicum virgatum		Moist, young forest
Paspalum notatum	h +	Successional
Paspalum setaceum		Loamy, frequent fire, successional
Saccharum alopecuroidum		Mature

Grasses	Training	Other significant relationships
Sorghastrum nutans	h +	Successional
Stylodon carneus		Mature
Tridens carolinianus		Successional
Tridens flavus		Successional
Tripascum dactyloides	h +	clayey, frequent fire
Triplasis Americana	L +	
Triplasis purpurea	h +	

Of the species present, most of the annual grass species were positively associated with heavy to intermediate training. These include sand sprurs (*Cenchrus longispinus*), Bermuda grass (*Cynodon dactylon*), crabgrass (*Digitaria* spp.), native and non-native love grasses (*Eragrostis* spp.), and non-native Bahia grass (*Paspalum notatum*). Interestingly, several common disturbance-dependent annuals such as smut grasses (*Sporobolus* spp.) and poverty grass (*Aristida tuberculosa*) did not have significant associations with military training.
Native old field and meadow perennial grasses like broomsedge (*Andropogon virginicus*), yellow Indian grass (*Sorghastrum nutans*), and eastern gama grass (*Tripascum dactyloides*), and redtop (*Triplasis purpurea*) were also positively associated with heavy military training. Little bluestem (*Andropogon scoparius*) was must abundant in intermediate training areas. These grasses, as well as their early successional counter-parts, are critical components to the upland system because they serve as "place holder" species for future systems and provide a critical "ecosystem service" of soil stabilization and reduced soil exposure in open, heavily trained areas.

Most mature forest species such as witch grasses (Dichanthelium spp.), plume grass (Saccharum alopecuiroidum), bluestems (Andropogon gerardii, A. gyrans, A. ternarius), switch cane (Arundinaria gigantea), Chasmanthium sessilifolium, three-awns (Aristida purpurescens, A. oligantha, A. longespica), Erianthus contortus, and Muehlenbergia expansa were associated with light training. These species as well as those listed as having very low frequencies (Sorghastrum secundum, S. elliottii, Sporobolus junceus, etc.) should be the target species for monitoring the advancement toward an improved pine habitat setting. These species are fire-dependent, they require open forest settings with limited shrub and mid-story, and they provide ample seed sources for granivorous species as well as fuels suited for low intensity fires.

Table 25. Legumes relationships with disturbance intensity.

Legumes	training	Other significant relationships
Cassia fasciculata	h +	Young forest
Cassia nictitans.	l +	Loamy, frequent fire
Centrosema virginianum	h ++	Loamy, frequent fire
Clitoria mariana	Intermed.	Loamy, frequent fire
Crotalaria spectabilis		frequent fire, early successional
Dalea purpurea	h +	
Desmodium ciliare	l ++	
Desmodium floridanum	l +	
Desmodium lineatum	l +	
Desmodium rotundifolium	L +	mature forest
Desmodium intermedia	l +	mature, longleaf forest
Desmodium strictum	l +	
Galactia microphylla		successional
Galactia volubilis		Successional
Kummerowia striata	h +	Successional
Lespedeza cuneata	h +	early successional
Lespedeza hirta	l +	Successional
Lespedeza repens	h +	
Lespedeza sp.		Loamy, frequent fire
Lespedeza stuevei	l +	Successional
Petalostemum pinnatum	l ++	dry, mature, longleaf
Rhynchosia reniformis	l +	Sandy, early successional
Rhynchosia tomentosa	h +	Loamy, mature, longleaf
Schrankia microphylla	l +	Loamy, frequent fire, early succ.
Strophostyles umbellata	l +++	Clayey
Stylosanthes biflora	l ++	Loamy, frequent fire
Tephrosia florida		successional
Tephrosia spicata	L +	clayey, frequent fire, mature, LLP
Tephrosia virginiana	Intermed.	dry, frequent fire, successional
Vicia sp.	h +	clayey, early successional

Many large-seeded legumes, such as Amorphas fruticosa, Amphicarpaea bracteata, Apios americana, Astragalus villosus, Baptisia alba, Baptisia albescens, Baptisia bractea, Baptisia lanceolata, Crotolaria spp., Galactia regularis, Indigofera caroliniana, Lupinus spp., Orbexilum pedunculatum, Pediomelum canescens, Phaseolus polystachios, and Strophostyles spp.

had very limited occurrences. Other important legumes, Desmodium and Lespedeza, had fairly low coverage and species richness relative to other locales. Walker (1993) found similar limitations in some areas elsewhere. Legume abundance is very limited at Fort Benning, generally 3X to 5X lower than other Coastal Plain areas. As a functional group they can play a critical role in N recovery following burning and supporting the overall health of the ecosystem and habitat.
Limited occurrences may be due to: (1) recent military training histories or the lack of dispersion back into areas modified by past 19th and early 20th century agriculture, (2) inappropriate conditions for seed germination due to fire conditions or high seed mortality, or (3) dispersal limitations.

Most legumes did not have positive relationships with heavy military training. Some exceptions include herbaceous vine and creeping perennials like vetch (*Vicia* spp.), *Lespedeza repens*, butterfly pea (*Centrosema virginianum*); non-native planted species like *Lespedeza cuneata* and *Kummerowia striata*; and low herbs like *Rhynchosia tomentosa*, *Dalea purpurea*, and *Cassia fasciculata*. Monitoring these species to assess impacts would be useful because these species tend to spread through sprawling or sprouting from a common base; therefore, are capable of quickly covering exposed surfaces. However, these species have fairly low N fixation rates, thus contribute little toward soil N storage.

The most characteristic legumes associated with mature forests and light training include summer farewell (*Petalostemum pinnatum*), *Tephrosia spicata*, *Strophostyles umbellata*, *Stylosanthes biflora*, as well as several *Lespedeza* and beggar-tick (*Desmodium*) species. The presence and abundance of these species, and those others listed (*Baptisia* spp.,etc.), are indicative of the impacts of training as well as habitat quality. Because of their importance to wildlife species, these species should also be actively restored in deficient areas.

Like the other forbs and grasses, several species traditionally associated with upland woodland and savanna settings had limited occurrence; therefore, though targets for recovery, had little statistical significance as “indicators.” These absent species are essentially “default” indicators of training or landscape influences, and across Fort Benning are generally restricted to “reference” areas (e.g., Unique Ecological Areas). Like the grasses, asters, and legumes, reestablishment of these species would likely require change in land-use patterns, active replanting & restoration, and in some areas, soil remediation. Some of these species include milkweeds (*Asclepias spp.),* jack-in-the-pulpit *(Arisaema spp.),* birthwort *(Aristilochia serpentaria),* fly-poison *(Amianthium muscitoxicum),* blue-star *(Amsonia ciliata*), smooth false-foxglove *(Auereolaria virginica*), devils-bit *(Chamaelirium luteum),* larkspur *(Delphinium carolinianum),* rattlesnake master *(Eryngium yuccifolium),* St.-Johns wort *(Hypericum spp.),* yellow star-grass *(Hypoxis spp.),*dwarf iris *(Iris verna),* pepper grass *(Lepidium virginicum),*wood lilies *(Lilium spp),* false-pimpernel *(Lindernia dubia), Ludwigia spp.,*loosestrife *(Lysimachia spp.),* sandwort *(Minuartia caroliniana)* ,evening primrose *(Oenothera spp).,* beard-tongue *(Penstemon australis), Phlox spp.,* fringed-orchids *(Platanthera spp.*), milkworts *(Polygala spp).,* meadow beauties *(Rhexia spp),*black snakeroot *(Saniculata spp.),* bloodroot *(Sanguinaria canadensis), Salvia spp., Seymeria spp.,* ladies-tresses *(Spiranthes spp.),* queens-delight *(Stillingia sylvatica), Stylisma pickeringii.,* meadow-parsnip *(Thaspium spp.),* bellwort *(Uvularia perfoliata),* and *Warea cunefolia.* In addition to these species, others associated with slopes, transitions, and lowland habitats are also commonly found within the system.

Though several species were present within all study sites, the above listed species are also important components for system diversity because they flower through out the growing season and offer alternative food sources for herbivores and associated fauna. For example, the lack of milkweeds (*Asclepias* spp.) on the landscape, essentially excludes monarch butterfies from the area. Therefore, the absence of these species equate to reduced insect diversity and opportunities for insectivores and other primary consumers. With consideration of the other species groups, ecosystem sustainability and efficiency is directly dependent of functional complexity. Few managers would argue that the great the numbers of food and habitat types within a management unit, the greater the number of sustainable game and non-game wildlife species populations. Therefore, management focus on a upland longleaf pine ecosystem does not prohibit opportunity for these other species groups at multiple scales; hence the focus is on the "matrix," whereby, concepts of uniformity at one scale accomodate heterogeneity at other spatial and temporal scales. The allowance for "worlds within worlds" expands the opportunity for these plant species and those that benefit from them.

Heavy disturbance was found to be benfitial to several early successional, disturbance dependent mostly perennial species that occur under different moisture settings. These include *Croton glandulosus*, *Commelina virginica*, cottonweed (*Froelichia gracilis*), poor-joe (*Diodia teres*), bedstraw (*Galium pilosum*), touch-softly (*Cnidoscolus stimulosus*), *Bulbostylis* ssp., yellow jassamine (*Gelsemium sempervirens*), frostweed (*Helianthemum rosmarinifolium*), orange grass (*Hypericum gentianoides),* morning glories (*Ipomea* pp.), Japanese honeysuckle (*Lonicera sempervirens*), *Mollugo verticillata*, may pop *(Passiflora incarnata) Pedicularis canadensis*, *Polypremum procumbens*, *Stipulicida setacea*, dawnflower *(Stylisma patens)*, and *Tragia urens*.

Interestingly, many first year annuals were not significant components of the disturbed sites. The listed species tend to be either upright forbs, or sprawling forbs and herbaceous vines. Like those listed with the herbaceous legume vines, these species influence future species establishment by shading the soil surface and climbing on existing vegetation. As indicators, comparison of these species with the amount of bare soil is an indicator of recovery. Training that enables repeated establishment of these species suggests that some level of soil rhizosphere health, which is important for the establishment of later successional species.

Table 28. Other forbs' relationships with disturbance intensity.

Other Forbs	training	Other significant relationships
Acalypha gracilens	L +	young forest
Agalinis purpurea	Inter-med.	moist, loamy
Agalinis setacea	L +	loamy, successional
Agave virginica	I ++	frequent fire
Agrimonia pubescens	Inter-med.	clayey, frequent fire, mature forest
Aletris farinose	L +	frequent fire, mature, longleaf
Angelica venenosa	I +	moist, frequent fire
Auereloaria pectinata	I +	Dry, sandy, mature forest
Bulbostylis spp.	H +	Early successional
Carex sp.	Inter-med.	loamy, frequent fire
Cladonia sp.	Inter-med.	dry, sandy
Cnidoscolus stimulosus	H +	dry, sandy, frequent fire
Collinsonia sp.	L +	moist, clayey
Commelina virginica	H +	frequent fire
Croton glandulosus	H ++	Moist
Diodia teres	H ++	sandy, early successional

Other Forbs	training	Other significant relationships
Epigaea repens	I +	sandy, mature, other forest
Eriogonum tomentosum	L+	Sandy
Euphorbia corollata	I +	Sandy
Froelichia gracilis	H ++	Successional
Galium hispidulum	I +	
Galium pilosum	H ++	Early successional
Gelsemium sempervirens	H +	sandy, infrequent fire, young forest
Helianthemum rosmarinifolium	H +	frequent fire
Hexastylis arifolia	L ++	moist, clayey, infrequent fire
Houstonia procumbens		moist, mature forest
Hypericum gentianoides	H +	dry, successional
Hypericum hypericoides	Intermed.	dry, infrequent fire, young forest
Hypericum stans		dry, infrequent fire, other forest
Ipomoea pandurata	H ++	Successional
Ipomoea purpurea	H +	
Ipomoea sp.	H +++	Early successional
Juncus tenuis		dry, frequent fire, mature forest
Lechea minor	I +	young forest
Lechea villosa	H +	frequent fire, early successional
Lithospermum caroliniense	H +	Dry
Lobelia puberula	I +	moist, loamy, mature forest
Mitchella repens	I ++	Mesic, sandy, mature, mixed forest
Mollugo verticillata	H ++	Early successional
Opuntia compressa	Intermed.	Dry, sandy
Osmunda regalis	I ++	moist, sandy
Oxalis sp.	Intermed.	loamy, infrequent fire, successional
Paronychia sp.	H +	Sandy
Passiflora incarnata	H ++	Successional
Pedicularis canadensis	H ++	
Phlox nivalis	L +	moist, early successional
Piriqueta cistoides		Dry, Successional
Polypremum procumbens	H ++	Early successional

Other Forbs	training	Other significant relationships
Pteridium aquilinum	I +	frequent fire, longleaf
Rhexia mariana		moist, mature forest
Ruellia caroliniensis	I ++	loamy, mature forest
Solanum carolinense	I +	
Stipulicida setacea	H +	frequent fire
Stylisma patens	H ++	Dry, sandy, successional, other forest
Tragia urens	H +++	Sandy, successional
Trichostema dichotomum	I +	Early successional
Urtica sp.	L +	moist, loamy, successional
Viola palmate	I +++	Longleaf
Wahlenbergia marginata	Inter-med.	Successional
Yucca sp.	Inter-med.	Dry, sandy, mature, other for-est

Several species that are often found intermittently, and scattered within burnt over upland forests were associated with intermediate or slightly associated with light training. These species include three-seeded mercury (*Acalypha gracilens*), *Agalinus* spp., soft groovebur (*Agrimonia pubescens*), colic root (*Aletris farinosa*), *Angelica verenosa*, false fox-glove (*Aureolaria pectinata*), *Collinsonia* spp., sedge (*Carex spp.*), reindeer moss (*Cladonia spp.*), trailing arbutus (*Epigaea repens*), dog-tongue (*Erigonum tomentosum*), *Euphorbia corollata*, *Galium hispidulum*, St.-Andrews cross *(Hypericum hypericoides)*, *Lechea minor*, *Lobelia puberula*, prickly pear *(Opuntia compressa)*, wood sorrel *(Oxalis sp.)*,*Phlox nivalis*, bracken fern *(Pteridium aquilinum)*, *Solanum carolinense*, blue curls *(Trichostema dichotomum)*,wood nettle *(Urtica sp).*, *Wahlenbergia marginata*, and *Yucca sp.*. Monitoring these species with asters has significant value because the presence of these species defines the differential effects between “light” training and “heavy” training. Therefore, the cumulative effects of repeated dismounted training are likely to be expressed as low levels of “heavy” training at plant appropriate scales.

Several species that are often found intermittently and scattered within burnt over upland forests were associated with intermediate or slightly associated with light training. These species include three-seeded mercury (*Acalypha gracilens*), *Agalinus* spp., soft groovebur (*Agrimonia pubescens*), colic root (*Aletris farinosa*), *Angelica verenosa*, false fox-glove (*Aureolaria pectinata*), *Collinsonia* spp., sedge (*Carex spp.*), reindeer moss (*Cladonia spp.*), trailing arbutus (*Epigaea repens*), dog-tongue (*Erigonum tomentosum*), flowering spurge (*Euphorbia corollata)*, *Galium hispidu-*

lum, St.-Andrews cross *(Hypericum hypericoides)*, *Lechea minor*, *Lobelia puberula*, prickly pear *(Opuntia compressa)*, wood sorrel *(Oxalis sp.)*,*Phlox nivalis*, bracken fern *(Pteridium aquilinum)*, *Solanum carolinense*, blue curls *(Trichostema dichotomum)*, wood nettle *(Urtica sp.)*,*Wahlenbergia marginata*, and *Yucca sp.*

Species strongly associated with light training include *Agave virginica*, heartleaf *(Hexastylis arifolia)*, *Osmunda regalis*, *Ruellia caroliniana*, and *Viola palmata*. These species are indicative of military training beyond “light” levels. These species are highly sensitive of surface soil disturbance or compaction. The presence of these species, and those listed as having low occurrence, indicate low levels of training impact.

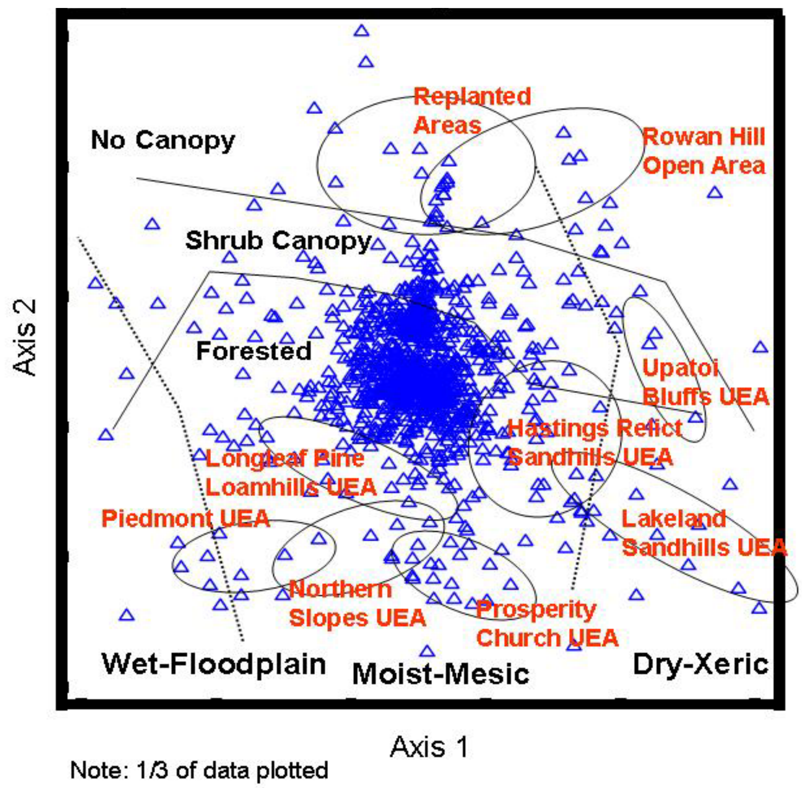

Figure 68. NMDS ordination of Fort Benning presense-absence ground cover data.

Using NMDS for multivariate ordinational comparisons, the collective SEMP ground cover data plus data from SI-1302 (Sharitz), land condition trend analysis (LCTA) and other Benning data sets, the data were compared using presence-absence information. The 1st principal axis was associated with moisture regime and soil texture (Figure 68). The 2nd principal axis reflects disturbance and canopy coverage. These categorical features are separated by dotted (moisture regime) and continuous (canopy cover) lines that reflect 90% membership. Also depicted on the figures are encircled (90% membership) areas representing data from seven Unique Ecological Areas and two highly disturbed study areas. The majority of the LCTA data is centrally clustered and reflects typical conditions on the landscape that are dominated by species associated with successional forest species. Interestingly, the fire-maintained systems occur between the successional forest LCTA data and the upland hardwood dominated sites. A similar relationship was also found in other SEMP studies. Relative to hardwood understories, this reflects the close relationship of fire-dependent species assemblages to other disturbance dependent assemblages.

Endangered, threatened, and species of concern

None of the SEMP studies were focused on compliance issues associated with Endangered, Threatened, and other Species of Concern; however, these studies were focused on the long term sustainability of conditions that would support these species and the implications of actions that would cause change. In the development of the RSIM model, some attempt was made to accommodate landscape level implications of land-use patterns on habitat suitability for the red-cockaded woodpecker (RCW). SERDP supported additional work to evaluate similarity and differences for the application of two feasible landscape models (RSIM, mLeam). These comparisons revealed that these models could be integrated as companion models if necessary, each had their own strengths and weaknesses and relied on different criteria that was derived from similar data sets (Dale & Westervelt 2007).

Another aspect of a SEMP funded study (SI-1114a, Dale) evaluated the impact of mechanized training on gopher tortoise burrow sustainability. Still another SERDP funded study (SI-1302, SREL, PI-Sharitz) had an objective focused on evaluating the impact of RCW management on other species of concern (rare plants, gopher tortoise). These additional studies were implemented through coordination with staff and SERDP. The latter project revealed that gopher tortoise and plant species of concern overlap in occurrence on the landscape, and their occurrence can be represented using landscape models, then used to identify high priority areas of conservation. Fine-scale model resolution can also be used to project optimum positioning within habitat areas for individual plant species. Through SERDP funding, other initiatives are underway to study interaction and connectivity of RCW and gopher tortoise populations.

6 Current and Future Research Needs

Administratively, an evaluation of how to incorporate research findings and identify research needs is required. Currently, adaptive management strategies are not emphasized in all programs and the incorporation of research is not well connected to management strategies. The below list of research needs should be evaluated based on the prioritized management goals and initiatives, the magnitude of risk, the likelihood of occurrence, and the potential for management to incorporate findings. This section does not prioritize these items, but rather from Fort Benning research and that conducted elsewhere in the region identifies current and future research areas that may impact Fort Benning compliance and sustainability.

Many of the research priorities identified below are consistent with those identified at a recent SERDP-sponsored workshop (HydroGeoLogic 2007). The identified research needs could be integrated with past studies and would likely benefit from those studies that provide baseline information that can be used to develop hypotheses, initial model parameters, and necessary context.

The interactive effects of climate change and training on landscape conditions and expectations

Increased training as well as climate change will add addition stress to most ecosystems. In most cases, both will result in reduced capacity to provide adequate ecological services (e.g., sustainable training lands, watershed protection, and habitat for endangered species). The combined effect is likely to be a magnification of impact of either individual factor. Further, change caused by either changing condition is likely to be accelerated by magnified effects.

Changing environmental settings through increased training or climate change may preclude a reassessment of desired future condition states. Though the longleaf pine upland matrix is a past steady-state condition (Frost 1993, Abrams 2002, Platt 2004, Peet 2006) and a desired future condition (INRMP 2001, 2006); it is still uncertain as to whether this ecosystem condition is the most sustainable military-use condition or expected state under climate change conditions. Some evidence from other locales, and including observations from 50 years of training prior to management toward pine savannas, suggest that hardwood rooting profiles may be better suited for military training activities in some areas.

Generally, hardwoods are recognized as having root systems that are proportionately deeper than surface rooted conifers; though longleaf pine are known for deeply rooted tap roots. However, various studies (Wells & Shunk 1931, Woods 1957, Boyer 1973, McGinty & Christy 1977) found that nearly all longleaf pine roots were within the upper 20 cm of the mineral soil, particularly in infrequenty burnt areas. Finally, urban foresters and planners have long recognized the adaptability of hardwood root systems to areas with restricted or compacted root settings.

From the stand point of global climate change and climatic ecosystem patterns, climate profiles would suggest that expected conditions are higher heat loading, less frequent storm events with higher amplitudes; this equates to reduced soil moisture, greater storm runoff, and additional moisture stress in the terrestrial habitats. Assuming patterning similar to other global regions, the sandhill region will slowly transition toward favoring sparsely vegetated scrub-shrub condition that has infrequently intermixed with infrequently treed grassland that has a super canopy composed of drought resistant pine trees (USFS 2001). Again, the long term outcome is highly dependent upon the magnitude and rate of change as well as the presence of a suitably adapted seed source. The direction of change may also be influenced by perturbation patterns; heavily or frequently disturbed areas, such as in some locales on military installations may begin changing earlier due to increased opportunities for establishment. This change may result in a different pattern of species assembly as well as different ecosystem trajectory rates and directions relative to other locations in the sandhills region. Thus, “end point” conditions for military installations may be different than those for the surrounding areas; either way, different priorities and concerns are likely to develop as well as different approaches to land management and sustainable training and military use.

Smoke characterization and fuels management

An integral part of RCW recovery and progress toward the longleaf pine upland matrix is related to the effectiveness, frequency, and opportunity of burning. Though fairly insignificant to the problem relative to direct human inputs, several concerns exist relative to the contribution of controlled and uncontrolled burning. In particular, PM2.5 and ozone are becoming increasingly important components of burn planning. Two primary concerns exist, regional contributions of smoke and local smoke effects on the community. Most of the regional contributions are contained within the "smoke plume" which is transferred at high elevations particularly during the active burn period during daylight hours. Most of the smoke associated with local settling, brought about by evening temperature change and heat inversions, is generated by post-fire smoldering of the 100- and 1000-hour fuels. Without weather change, this smoke can persist or "laydown" locally for many days and is enhanced by continued smoldering. It is known that woody fuels (mid-story, standing and dead trees, downed material, etc.) contribute more heavily to controlled burning concerns than do flashy fuels such as grasses, herbaceous plants, pine straw, etc. Expected progress toward an upland pine matrix dominated by grassy fuels should improve smoke emission problems; however, significant progress may require time frames that are beyond compliance and community tolerance levels.

Fuels management and characterization of expected post-burn smoke patterns is a developing issue that requires critical evaluation and comprehensive understanding for effective RCW and longleaf pine management. As a component of this need, better characterization of conditions and association with remote imagery is needed to effectively represent installation wide conditions. Part of this characterization should include accurate measurements of existing fuel types, fuel amounts, and the effectiveness of burning.

Several research areas currently exist: (1) what regional contribution does controlled burning make relative to uncontrolled wildfires (which on military installations have high likelihoods), (2) how can incipient post-burn smoldering and local "settling" of smoke be better regulated and reduced through burn timing, ignition strategies, multiple-burn aggregation, and interpretation of expected weather patterns, (3) can fuels management toward a grassy condition significantly reduce PM2.5 contributions, (4) can progress toward desired fuel conditions be accelerated by active understory restoration, (5) how will expected development around Fort Benning and potential change in air quality regulations influence burn patterns and achievement for the recovery of RCW populations, and (6) with expected climate change, how will burn opportunities change and how will this be incorporated into burn planning.

Forest health risk

Maintenance of existing mature pine forests is paramount to RCW population recovery and progress toward attainment of upland pine matrix DFC's. For various reasons (site history, training impacts, soil quality, past land management actions), several forested areas are exhibiting elevated loss of mature trees. Because forest health problems can often be rectified, if detected early enough, quantifiable and reliable remote and on-site detection techniques are critical needs of land management personnel. A recent SEMP-sponsored workshop suggests that increased monitoring and research of forest health issues at Fort Benning should be implemented. This workshop did not reveal findings of immediate concern, but did clearly identify elevated mortality at Fort Benning and associated risks if recent mortality patterns continue and spread elsewhere or into other high-priority ecosystems (e.g., young longleaf pine).

Secondly, diagnosis and evaluation of the problem is important. This often requires forest health and pathology specialists that can diagnose problems. Proper diagnosis is critical because it often alludes to conditions that allowed pathological conditions to develop and it allows for proper proactive actions to avoid further expansion of the problem. Finally, proper diagnosis is necessary to detect whether the problem is a newly developing condition, such as through the establishment of non-native invasive pathogens, or for identifying a typical condition that has been magnified by additional stressors.

Finally, early detection criteria for field diagnosis of potential forest health problems (IPS beetles, turpentine beetles, southern pine beetles, *Leptographium* spp. Fungi, *Anosym* root rot, little leaf disease, *Fusiform* rust, etc.) is important for developing early detection land management strategies and assessing the likelihood of pathogenic problems. Field identification of problems is also important for regional initiatives in evaluating areas of potential concern.

Future research should consider the differential effects of climate change on species and landscape settings. Pitelka (1999), Otrosina et al. (2002), and others have identified reduced forest health and tree longevity as one of the precursor indicators of climate change. At the landscape level, what should be evaluated is the identification of areas that are most prone to drought stress; hence, areas of expected loss of root health and vigor, therefore, root susceptibility. This effort should include an evaluation of which pathogens and disease vectors are expected to be most opportunistic in drought prone areas. This research, could lead to the identification of landscape settings and forest conditions that are most prone and should be avoided relative to additional stress that may impact root and tree health (e.g., mechanized training, unregulated burning). This information could also be used to help prioritize the conversion toward more appropriate drought-tolerant species (e.g., longleaf pine).

Endangered species risk, management, and interaction

Currently, the spatial dynamics of RCW recovery is based on existing RCW group locations, existing and potential future habitat, and expected military training needs. Potential vegetation is obviously defined by need but should consider capacity and potential natural vegetation patterns. These classifications, based on regional and local initiatives by The Nature Conservancy, do currently exist and could be used to identify potential future bottlenecks for RCW recovery. These classifications, and historic fire regimes, are being further evaluated by various contractors (e.g., Cecil Frost). Collectively, this information could be modified to represent system vulnerability, and when spatially expressed, used to guide management priorities.

Continued research is needed to evaluate whether RCW recovery-associated management is beneficial to other species of concern. Various species are subject to the criteria associated with RCW recovery; when applied at the landscape level these criteria minimize variance of condition and likely reduce habitat suitability for some species. It’s important to know these effects for species of concern as well as characterizing species. It should be noted that at some scale variance is retained; for example, at scales larger than management units and smaller than typical management actions (e.g., hardwood densities are too diffuse to initiate management action, small hardwood inclusions).

The recovery and stabilization of gopher tortoise populations is critical to the interest of military installations because training-use conditions and patterns closely reflect those conditions used by gopher tortoises; thus, listing of the gopher tortoise would greatly hinder military installation land-use. Though some issues have been well researched, several issues remain. Continued studies of gopher tortoise habitat characterization and use are needed relative to military training land expectations. Further, these studies should consider connectivity between population groups and the identification of potential areas between population groups that can be used for periodic training as well as individual gopher tortoise movement and habitat exploration. Some concerns have been raised that military training has differential impacts on certain size and age groups, in particular juvenile survivorship. Studies are needed to both improve survivorship of “at risk” age groups as well as studies designed to evaluate the implications of elevated losses of juveniles. Finally, continued research is needed to evaluate effective translocation and group establishment, these studies should include issues a) related to minimum group size establishment, b) interaction between non-group members with establish group membership, and c) continued evaluations of the implication of the spread of lethal and non-lethal disease vectors into previously unaffected population groups.

Feral hogs pose an increased threat to gopher tortoise and plant species of concern as well as other listed species. Increased training use of Fort Benning is likely to subject the remaining forested areas, including transitional hardwood and riparian hardwood systems, to increased feral hog damage. At present, the elimination of feral hogs from Fort Benning is not an achievable goal because of emigration from nearby areas and the existence of impact areas that serve as refugia for feral hogs. Further, because of high reproductive capacity a small residual population of feral hogs can quickly mushroom into a large problem. Feral hogs are know to selectively root certain species in a variety of areas, this behavior threatens rare plants directly through removal and indirectly through the creation of germination sites for early successional and invasive species. Feral hogs impact gopher tortoise populations via excavation and consumption of tortoises, particularly juveniles and eggs. Feral hogs also alter ground covers which may impact gopher tortoise diet. Finally, feral hogs commonly “till” small stream bottoms and streambanks during periods of low flow and exposure; the exposed and loosened sediment as well as excrement are then transferred down stream during storm flow and elevated flow periods. This poses a potential contaminant and human health risk (fecal coloform) as well as contributes to existing concerns associated with sediment transfer & loading, stream stability & capacitance for ecosystem services, and aquatic biota tolerance & assemblages. Research is needed to a) better evaluate the impacts and risks associated with the presence of feral hogs, b) improved control methods and seasonal periods of effective control, and c) mitigation techniques that can reduce the impact of feral hogs.

Other invasive species are of significant concern relative to rare species population maintenance and management. Though most invasive species displace other species causing a direct reduction in diversity, and indirect change in community components that are reliant on those species, species of particular concern are those that change system dynamics. For example, Chinese privet (a broad-leaved evergreen shrub) is highly capable of rapid expansion in bottomlands and altering nutrient transfer from the terrestrial watershed into wetland areas and streams. Broadleaf evergreen fuels beneath closed canopies also influence fire behavior due to high ignition temperatures. Privet, because of dense evergreen cover, also alters habitat suitability for many fauna species (e.g., oven bird) as well as feeding habits and success rates of carnivores (owls, snakes, mammals) that regulate rodent populations. Further, habitat use is shifted by changes in available seasonal patterns of food types for granivores and fructivores (dominated by waxy coated privet fruit that is available during the winter months). Along with privet, other species are known to have similar or greater effects of habitat quality & species use, nutrient & carbon dynamics, and fire behavior; these include Nepalese browntop (*Microstegium*), cogon grass, tallow tree, kudzu, and others.

Connectivity of populations is important for both the rare species and those species that are necessary for the capacity of life (habitat, food, dispersion, pollination, etc.). For example, *Trillium reliquim* has specific habitat conditions and requirements; but because particular ant species and sub-surface biota are important for seed preparation and dispersion, maintenance of suitable habitat for those species is also important. In particular, the native ant species involved in seed processing and dispersion are influenced by invasive fire ant species in some locations. Similar concerns exist for other rare biota. In the broadest sense, isolation and connectivity are issues because of its influence on population recovery as well as necessary genetic exchange, which is critical for long term population viability and adaptiveness through population level phenotypic plasticity and gene pool complexity. Connectivity is also important for optimizing the use of available habitats; obviously, having several populations of a rare species provides greater flexibility to land managers and training planners when populations are scattered populations exist across the landscape. To achieve these patterns and allow for natural patterns of emigration to establish new populations, isolation and barriers to dispersion must be minimized. Obviously, promoting connectivity with off-post populations is necessary for these same reasons. For most species, the level of fragmentation that results in isolation is not well understood, and remains as a critical need for rare species management across the southeast. For the sake of efficiency and timeliness, efforts to understand fragmentation effects should be coordinated through partnerships and shared with other interested land management agencies and groups.

Habitat suitability and maintenance for aquatic species, particularly bivalves and gastropods, is a significant future concern for Fort Benning and the Chattahoochee drainage. Increasing interest in listing many of these species for protection by state and federal agencies has elevated concerns about the lack of understanding of the needs of these species, habitat characteristics that are necessary for these species, and the occurrence of these species in existing stream segments. Further, the influence of land management and military training on these factors is even less understood.

Finally, potential climate change will magnify the needs of proper understanding of the requirements for these species and proactive adjustments to the management action for these species will become increasingly necessary to maintain progress toward recovery and compliance with agreed upon responsibilities for these species. In fact, many climate change models suggest that new “successional end points” may need to be considered. This possibility will complicate expectations because ecosystem and communities are less likely to shift in distribution “intact” and more likely to reassemble and develop into new ecosystem types that have different criteria and management needs.

The rhizosphere environment and soil biota

The role of the rhizosphere community in maintaining sustainably suitable conditions for upper plants and their supported ecosystem is a critical and often overlooked ecological service. The rhizosphere provides seasonally appropriate levels of mineralized nutrients in proportions roughly correlated with amounts associated with existing biomass inputs. Further, decompositional bi-products are more stable forms of organic material; therefore, is a critical component of nutrient and moisture storage (Garten and Ashwood, 2004). Like most components of an ecosystem, a critical element of the rhizosphere is the efficiency in transfer, processing, and storage of necessary or limited renewable and non-renewable ecosystem resources across a variety of potentially occurring spatial and temporal range of activity thresholds. The range, response, and efficiency therein of the rhizosphere to environmental conditions reflect patterns of diversity and dominance (Dale et al. 2005). An important aspect of the rhizopshere is whether bacteria or fungal hyphae dominate the decompositional process and rhizosphere setting. Obviously, within these general groups are different species with differential interactions with the environment as well as unstudied interactions and ties to other elements of the ecosystem (e.g., subterranean insect communities).

Reported from the initial SEMP studies was a decline in rhizosphere complexity. This assessment is generally based on genetic information and is potentially inclusive of a several interacting rhizosphere guilds and life form types (Peacock 2006, Zak 2006). Typically, fungi dominate the rhizosphere in acidic settings, such as beneath pine canopies; fungi are most efficient when C:N ratios are near 16.0, while a bacteria-dominated rhizosphere is most efficient with ratios near 8.0. Relative to the bacterial community, fungi are typically more impacted by reduced oxygen levels or significant soil disturbance. The resilience of the bacterial community is primarily due to the bacterial diversity through the presence of inactive bacterial forms that can quickly respond to changes in the soil environment; thus, readjust activity rates within the soil. This suggests a need for continued evaluation to determine the implication of rhizosphere composition and biomass (ie. Is higher rhizosphere biomass positively related to some aspect of productivity, efficiency, or sustainability; if so, what can be done to facilitate rhizosphere health).

Based on three SEMP studies, most Fort Benning upland forest areas have C:N ratios range between 25.0-30.0. These values are slightly higher than, but statistically close to, those from other Coastal Plain and Sandhill province areas (Kovacic et al. 1987). SEMP study soil C:N:P ratios and foliar nutrient content are strongly reflective of nutrient limitations, and suggest that N and P appear to be limiting growth. As noted, these numbers suggest that neither group is near optimum, bacterial activity is much less than optimum, but better suited to frequent or intense disturbance. Two questions are apparent, does rhizosphere health equate to short-term or long-term ecosystem health and sustainability and what values of C:N:P are attainable, sustainable, and relevant to ecosystem health.

Based on SEMP observations, highly disturbed areas have less genetic complexity/diversity. What hasn't been determined is if this is due to a) a restructured, simplified food web that is equally efficient, just different, b) loss of species or species-phenotypes that are either intolerant or inefficient within the range of characterizing conditions, c) reduced genetic diversity due to isolation, limited survivorship, and limited exchange that may have resulted from limited survivorship in adjacent areas or limited transference across hostile habitat boundaries. Essentially, low genetic diversity may be due to either loss of guild and food-web complexity or local "island" effect. Certainly, the latter has much stronger implications in that it implies that temporally or spatially habitat conditions are so hostile that biotic support is limited.

Carbon sequestration and storage

General estimates of carbon and nutrient loading for the installation can be made using a logical series of general ecosystem and forest type classifications, approximations of soil carbon using general soil classification and application of the Century model (Liu 2002), forest inventory data and allometric equations to estimate above- and below-ground biomass for forest, and regional estimates of productivity and loss. Much of the SERDP funded SI-1547 research (Liu, USGS) is focused on this approach with application to Fort Benning conditions. This approach can be further applied using Linkage-based models (Pastor & Post 1985) to estimate change in carbon stocks with forest development, changing CO_2 conditions, or climate. These models can then be extrapolated to regional scales using estimates of process rates and stocking levels across the region.

Research needs concerning the transfer and storage of carbon in wetlands remain an issue; particularly, from the standpoint of potential saturation, and associated implications, of wetland storage mechanisms. Generally, wetlands function as carbon "sinks" that store locally generated fixed carbon as well as that transferred from the surrounding terrestrial habitats. However, like most systems a point of "saturation" does exist and is comparable to issues associated with biotic waste treatment sites (e.g., eutrophication).

Research is also needed to characterize changing below ground carbon cycling with emphasis on root turnover, rhizosphere carbon processing rates, and the impacts of changes in soil biota that affect nutrient and carbon storage and cycling. Expected climate change will have predictable impacts on root turnover rates; in temperate settings, elevated soil temperatures will result in reduced root "half-life" which will cause additional allocation to root systems for maintenance and replacement, thereby potentially reducing allocation to aboveground growth (e.g., reduced tree growth). Further, species-specific root profiles will be differentially affected, causing some species to be more susceptible to drought.

Expected climate change patterns of prolonged droughts, heavier storm events, and greater seasonal variability will also effect surface processing of litter material. Extended droughts will result in reduced litter decomposition rates which equates to reduced nutrient turnover, reduced soil and nutrient surface storage capacity, and fuels build up. With fuels build-up less exposed soil will be present between fire events (thus, lower opportunities will exist for the establishment of mineral soil germinated grasses and forbs) and when burnt, higher fire intensity will result in greater canopy loss and greater volatilization of nutrients. Therefore, the regulating effects of frequent periodic fire will become even more critical; though the number of "suitable burn days" will be reduced and there will be increased concerns of C-input from fire and escaped fire "risk."

With continuing concerns over carbon budgets and concepts associated with "carbon credits"; a better understanding of carbon cycling as well as export and input is necessary to government agencies. Potentially, government- and state-agencies may need to further characterize their role in carbon cycling and make adjustments to landscape carbon input and export. These changes could further restrict or adjust land management and military training priorities.

Terrestrial nutrient balance and dynamics

Because of its direct ties to life efficiency, productivity, and performance, most nutrient studies emphasize the importance of N dynamics. Though countless studies have directly related N dynamics to patterns of individual, guild, and system productivity; a balance with other macro-nutrients is critical to life function. In fact, outside of moisture limitations, long growing seasons and other characteristics of the warm temperate systems result in N being less limited by fixation and mineralization, and more limited by competition and combustive loss.

Relative to terrestrial plant communities, phosphorus and potassium can be limited in harsh settings, particularly those with very low CEC and AEC as well as infrequently burnt systems that have organically-bound reserves. Like many agricultural systems, natural systems can be limited by phosphorus and potassium, and when limited affect are seed set and quality (Markewicz et al., 2002). Therefore, P and K availability and nutrient holding capacity are important attributes in areas that expected to naturally reseed and recover. These areas would also include intermediate-use or infrequent-use areas that may have issues associated with chronic sustainability and recovery; whereby, limited soil organic matter (with or without surface litter) may be a critical factor associated with P- or K-dynamics. These and other potentially limiting elements (Ca, Mg, Mn, etc.) are essentially earth-borne, total soil content of these elements is greatly influenced by exchange and storage capacity associated with fine-charged particles. Therefore, surface erosion and loss or compaction of fine material is likely to directly portray resource availability relationships. Phosphorus is often limited in wetland and aquatic environments, therefore, limited availability may affect system efficiency. Potassium availability has also been linked to forest health and susceptibility to forest health problems (Markewicz et al., 2002).

Like all ecological processes, expected climate change will cause shifts in ecological processes. For example, eventual elevation of soil temperatures will accelerate decomposition and nutrient release rates during seasons with sufficient moisture; therefore, nutrient availability may no longer coincide with peak nutrient demand. In the case of earth-borne nutrients, this will likely equate to reduced nutrient-use efficiency, greater system loss to aquatic systems, and a greater likelihood of that productivity will be limited by nutrient reserves. Changes in land-use patterns will also reduce nutrient storage within watersheds and increase nutrient loading into wetlands, and potentially stream systems. Further, if expected predictions are true, a greater frequency of intense storms will lead to greater bulk transport (erosion, litter transport) of nutrient reserves as well as additional leaching of readily-available compounds from the soil. Therefore, causing a further reduction of availability and balance of earth-borne macronutrients

Nitrogen dynamics and leads to sufficient availability in appropriate time frames have been linked to productivity by a variety of studies in the temperate and warm temperate regions. Because both nitrogen and sulfur have atmospheric cycling processes that return N and S to the terrestrial environment; absolute loss of N and S from the system is unlikely with temperature increase. In fact, activity that results in fixation of atmospheric sources is elevated with increased temperature and could potentially lead to saturation. However, influential processes of other soil chemistries (redox, pH), plant uptake, periodic burning (loss of volatile compounds) and variability in weather pattern regulate these compounds, and in the case of N, result in high competition and conservation of N forms. Often, nitrogen is the most limiting factor to productivity, particularly in frequently burnt areas. The influence of climate change however will change the dimensions of nitrogen cycling and with a high likelihood of new rate limiting steps that govern N availability. Like other nutrients, strong storms will result in greater loss through bulk transport of eroding surface soils as well as increased leaching losses. However, long periods of drought will likely reduce nitrogen fixation rates and, through the build-up of litter caused by slowed decomposition, because a reduction of nitrogen release from organic sources due to increased C:N ratios. This problem would be further exaggerated if there is an increase in sclerophylly (Chapin 1980, Burk & Vitousek 1984), and that is often the case as systems proceed toward infrequent, high intensity rainfall patterns (Barbour 1991).

The compounding influence of military land-use with climate change is obviously not known, but critical to the assessment of potential future-use patterns as well as appropriate training environments. Because nutrient cycling involves a series of complex processes, improved experimentally based evaluations are needed based on site-specific criteria that reflect future, current, and past land-use. Shifts in processes in the outer Coastal Plain (e.g., Camp LeJuene, Eglin AF Base, Fort Stewart) whereby weather patterns are strongly influenced by oceanic doldrums may be non-reflective of shifts in more inland areas (Fort Jackson, Fort Benning, Fort Gordon). These relationships are further complicated by differential military land-use patterns and expectations. Therefore, an improved understanding of nitrogen dynamics, particularly below ground and surface processes, are needed.

Fauna indicators

Various fauna use multiple components of a habitat or a variety of habitats. Some species such as Bachman's sparrow (pine savanna, early pine regeneration) and Swainson's warbler (open bottomlands with switch cane understories) have fairly specific habitat requirements that can be met by only a limited number of management options. Others such as many breeding neotropical migratory birds have fairly general habitat requirements (e.g., many warblers are associated with bottomland forest) but require large continuous areas that are suited to support multiple nesting pairs. Still others are highly dependent on corridors and connectivity between habitats for feeding (e.g., butterfly species). Though at a small scale, ants reflect both biotic (food) and abiotic (soil condition) aspects of locations.

Advantages to advancing the knowledge and understanding of fauna, and the possibility as potential management indicators, have long been recognized; a) they are responsive at spatial scales consistent with management activities, b) they integrate habitat structure, setting, and plant composition, and c) they tend to be rapidly responsive to change. In contrast, plants tend to respond to highly local changes and will often persist through disturbance; however, plants are much better indicators of chronic impacts as opposed to spatially or temporally acute shifts in the environment. Therefore, rapid biological indicators should emphasize responsiveness of the faunal community and assessments focused on chronic or legacy impacts should focus on assemblages of plants which, with abiotic measures, can be cumulatively used to project habitat quality for associated faunal assemblages.

Using fauna as indicators poses some problems; generally the best understood and most reliably present animal communities and species are not those associated with compliance concerns. However, what is needed is a step-wise connection from indicator response to compliance or sustainability concerns. In some cases, these relationships are understood or at least the potential effects clearly characterized (e.g., loss of pollinator groups). The benefit of using faunal communities is that they rapidly respond to acute change (e.g., forest clearing) through habitat choice criteria. Another benefit, unlike plant community sampling, is that sampling can be conducted in fairly short time frames (e.g., morning breeding bird census, insect traps, etc.); therefore, conflict with military training needs are minimized. Effective and efficient use of animal indicators or indicator groups should consider multiple scales that can be cross-linked to observed landscape patterns using remote imagery. Past research have focused on multiple groups that have included cow bird frequency (Tewksbury et al. 2002), neotropical breeding bird populations (Partners in flight, 2002), overwintering resident birds (Kilgo 2000), ant communities (Kryszik, unpublished), snakes (Siminlish 1994), and butterflies (Haddad 1998). Research is needed to develop cross-links with imagery information as well as between biotic groups. Further, research is needed to better characterize indicator response variables and then develop spatially-explicit models that have capacity to extrapolate these criteria across the landscape, and associated plant community conditions, to represent conditions in inaccessible areas (e.g., military impact areas).

Continued research is needed to evaluate plant indicators and indicator groups because plants, and plant community characteristics, are capable of representing chronic change and sustainability of those conditions. SEMP research identified several life form groups and families that are responsive to acute and chronic effects of military training. A better understanding of why these groups respond to these conditions is needed to better evaluate the impacts and expected post-disturbance change. The relationship of certain life form groups (e.g., therophytes (annuals)) to disturbance is understood; however, the scale and rate of potential response (1 Ha, 10 Ha, 100 Ha, etc.) is not well understood or predictable (Odum 1961, Golley and Pinder 1988). Like animals, generally the best indicators are not those that are associated with compliance concerns; however, the do collectively reflect functional efficiency and predictable successional trajectories that will develop future-use conditions. The loss or advancement of certain species, families, and life form groups has compounding impacts on future habitat types and associated roles on the landscape.

With advancing technology and increasing land-use and training demands, adequate on the ground monitoring is unlikely to be attainable without the development of forecasting models that are based on remote imagery and detection devices. Further, broad scale concerns are difficult to assess without the use of these technologies. A critical need is better establishment and identification of criteria that allows for scale-expansion from local level dynamics to regional concerns. With that scaled expansion, connectivity of relevant attributes is necessary. One issue of concern is the limited capacity to monitor fragmentation at multiple scales that are reflective of conditions and responsiveness of multiple species. Currently, multiple sources of remote sensing information are available but questions concerning the most appropriate scales have yet to be evaluated, or have the specific criteria for monitoring been identified. Another important issue is to improve the characterization of “within polygon” conditions to reflect desired and natural levels of heterogeneity that best suites ecosystem function. Better characterization of “between polygon” transitions and expected transitions is also needed. Finally, better associations between field monitoring and remote sensing observations are needed with emphasis on priority concerns.

A dispersion and home-range model for all species is needed. As a starting point, the relationship between body size and home range could be modeled, tested, revised, then projected across the landscape to look at how land-use change results in shifts in habitat connectivity and composition. Theoretical models and some application examples exist elsewhere, and with the BRAC process expected landscape changes are forecasted, and implications of those changes, could be tested with additional faunal information. One would expect the body mass relationship with home range to be strongly associated with niche and habitat quality; therefore, representative faunal groupings could be defined and used to assess change.

Water quality

Ongoing research needs include a continued evaluation of training impacts on hydrologic pattern, sediment, and stream quality (e.g., biota, chemistry, etc.). This research should be nested with existing and developing watershed models (BASINS model, SI-1147). In particular, model estimation and observed values in a step wise manner to determine deviations from expected conditions. These differences between model prediction and observation can then be assessed using multivariate characterization of secondary effects. These studies should also focus on the impact of off-post development, resulting hydrologic change, elevated potentials for fine sediment input, increased risk and rate of bed sediment (sand) movement, and the collective impacts on local habitat condition and capacity as well as the Chattahoochee drainage.

Similar continued research is needed to associated weather station observation and stream flow as a covariate function of training intensity and scale. Further, these associations are needed to forecast potential climate change effects during the recent past and predict future stream flow patterns. Collective estimates should be used to predict sediment and chemical contributions to the Chattahoochee River and then be validated by cooperative or existing measurements made above and below primary stream inputs (e.g., Upatoi River drainage). These estimates are necessary to evaluate the impact of Fort Benning activities on the Chattahoochee River drainage and associated increases in water demand. Finally, better characterization of installation-wide ecosystem services is needed to assess the regional role at watershed scales of Fort Benning relative to the storage, stabilization, release, and transfer of compounds and materials. Characterization of the quality and condition Chattahoochee River above and below Fort Benning is needed. These studies should consider the past- and current impacts of regulated water flow and hydroelectric impoundments. All of these factors have direct implications toward current and future capacities to support and maintain multi-faceted biological and socioeconomic functions.

Improved understanding of potential point source and non-point source inputs of contaminants is needed. These inputs and risks include munitions residue, human waste, fine and course sediments, fuels and other organic contaminants, and pesticide-use (e.g., herbicides). Besides risk modeling, better site specific techniques are needed to mitigate and avoid potential long-term and short-term filtering and movement of contaminents into and through wetlands. These studies should include potential risks of contaminent movement through bulk transport (erosion) of materials. Similar studies are needed to identify existing and potentially changing inputs associated with off-post watershed development.

Changing climate is likely to magnify existing problems associated with drainages within and along Fort Benning. Properly functioning riparian zones are critical to flood control and water storage. Elevated temperatures and chaotic weather patterns are likely to magnify the variance in streamflow. These changes are likely to exceed biological thresholds for many species. The limit or loss of some species may reorder functioning food webs are result in a decline in biological function. The result reduced stabilization and processing of materials, lower threshold capacities, and a decline in materials (carbon, nutrients) storage. Therefore, understanding the biological effects of these changes will allow for more accurate evaluations of expected capacitance of systems to adjust to additional input from the surrounding terrestrial watershed component.

Because of past- and current management, wetlands and aquatic systems are highly susceptible to invasion by exotic species (e.g., zebra mussel, bighead carp, Eurasian milfoil, etc.). Therefore, it is necessary to accurately evaluate the potential impacts of these species. Further, better characterization of system susceptibility is needed; these characterizations should emphasize past and current conditions and focus on identifying avoidance criteria that will limit establishment or impact of establishment. These research initiatives should also evaluate potential mitigation actions and techniques to avoid establishment of these species.

Several unknowns associated with stream function and its association with composition, diversity, and food web complexity still exist. Generally, increased biological diversity and food web complexity equate with higher rates of the conversion of coarse organic debris to fine material and then organic compounds which are transferred or stored. Studies that directly associate these relationships with compliance and risk issues continue to be needed.

Further, SEMP studies and others have established that maintenance of biological diversity can be improved through amendments with coarse woody debris. This material expands the number of habitat types and proportions and allows for elevated species richness. However, from the standpoint of optimal use of this material, strategies for placement, variability of type and size, and replentishment have not been developed. Further, because of flashy hydrology and burial by sediments, techniques and methodologies for permanent placement of coarse woody material into the streambed also requires continued reseach and development.

Wetland function and condition

Stream wetlands and riparian areas are seldom used for military training and receive little attention through land management activities. Essentially, stream bottoms and riparian zones are passively managed except for considerations involving stream crossings or issues related to compliance with the wetland protection act. Though little used, Fort Benning wetlands and riparian forest remain a critical landscape component because of alternative habitat conditions, connectivity to other systems, and functioning as a storage “sink” of terrestrial input that protects aquatic systems. Undoubtedly, SEMP studies found, as other many studies have, that frequent crossings by roads, trails, etc. or direct input of materials via erosion diminishes water and stream quality.

Like most wetland systems in the surrounding area, Fort Benning are composed of aging secondary successional forests that compositionally reflect establishment conditions and sprouts from formerly dominant species. For the most part, the canopy of these systems was selectively harvested resulting in the removal of desired species and large marketable individuals, leaving behind potentially genetic inferior individuals and opportunistic successional species. The understory is likely to have been left relatively intact, except in areas used for agriculture by Native Americans. However since establishment, particularly along the river course, flood control features are likely to have changed the regulating dynamics that formerly influenced the successional progress of these systems. Therefore, the remaining adhoc compositions are adequately functioning but potentially could be improved from the stand point of ecosystem efficiency and habitat continuity with the landscape. Like all systems an evaluation of the current and expected capacitance of the wetlands to withstand continued change without significant loss of ecosystem function, progress, and services is needed. Part of this evaluation should be realistic consideration of the effects of sedimentation, hydrologic change, continuity of composition over time and space, and potential risks of invasive species establishment. Further, research is needed regionally to consider when the harvesting risk to improve ecological function exceeds the likelihood of improvement. Part of this consideration should be the changed hydrologic regime, the likelihood of invasive species establishment, and the potential for a temporary reduction in ecosystem quality and function.

Isolated wetlands are an uncommon but important feature at Fort Benning. Currently, these systems need better characterization, assessment, and integration into the landscape matrix. Further, these systems are threatened by invasive species, the lack of past management, and inappropriate military-use. Additionally, climate change may impact these systems through impacts on seed persistence and dormancy. Elevated soil temperatures and fluctuations of soil moisture threaten the capability of buried seed to break dormancy and become established. These threats exist in both isolated and alluvial wetlands, but are of particular importance to isolated wetlands due to limited seed migration and the dependence on fire to stimulate germination. Many understory plant species are capable of prolonged persistence in the seed bank (e.g., *Rhexia, Sagittaria, Croton*), but rhizosphere changes may potentially limit this capacity because of elevated seed respiration and dessication. Investigation of these research areas is important to improve habitat expectations and definitions of species suitability. Many of the impacted species are likely to become rare; therefore, may become future compliance issues that impact military land-use.

Climate change effects in wetlands are also likely to impact other species groups such as amphibians. Amphibians are likely to be impacted because of changing conditions that are inconsistent with annual reproductive cycles and timing of many species. Populations of these species will also be impacted by year-to-year changes in hydrologic settings and burn regimes.

These effects are not limited to herptofauna, asynchronous timing or altered biological timing schedules of other species (insects, plants, migrating birds) will also be effected and result in reduced functional efficiency and lowered biological diversity. The life cycles of most terrestrial, wetland, and aquatic species are highly dependent on predictable settings that support synchronized flowering, breaking dormancy, life cycle advancement, and movement into and through habitat areas.

Ecosystem assembly and reassembly sequences as related to military activities

Several ecological indicators and thresholds were identified by SEMP research. Somewhat expectedly, no one ecological indicator is sufficiently capable of addressing all potential aspects of ecological change that may arise from various disturbance vectors. Therefore, effective use of ecological indicators will require a multi-disciplined approach. What has yet to be evaluated is the relationship of these indicators, and the ecological problem that they identify, to ecological risk. Therefore, risk analysis using a cost-benefit approach is needed to prioritize indicator use and problem assessment as well as scaled operational reaction to the problems. For example, if water quality issues and RCW recovery were compared the risk and cost associated with each compliance concern would likely differ. Water quality risks are likely to be very low, but have high costs direct and indirect costs associated with this risk. On the other hand, failure to recover RCW is likely to have slightly higher risk, but lower long term costs. Therefore, when developing a monitoring program what indicators should be emphasized and which should be considered to have lower importance. Further, “risk” should be addressed from the stand point of both long term planning (e.g., climate change effects) and short term operations toward compliance and sustainability (e.g., land-use change that results in the inability to adequately maintain burn regimes to support RCW recovery).

Continued research is needed to evaluate whether degrading or degraded ecosystems disassemble in the same sequence as is needed for reassembly. This research is needed to both detect the loss of ecosystem function in actively used areas (e.g., military training areas, urban expansion areas). Various SEMP and outside research studies have indicated that the most typical trend is rapid conversion from one state to another with declining function. Understanding of these processes is necessary to maintain future land-use opportunities and sustainable training. In particular, it is necessary to keep the effects of past and on-going heavy training and land-use to the local area, and minimize the lateral expansion of these problems into adjacent areas (e.g., lost capacity to carry fire, loss of function and connectivity); these phenomena are often driven by positive feedback mechanisms that facilitate the gradual expansion into adjacent areas and nearby drainages. Secondly, the collective loss of ecosystem function in terrestrial areas results in over-burdening input of materials and compounds into associated wetland and aquatic systems.

This information is also valuable in areas being rehabilitated or restored (e.g., military areas that will no longer be heavily used). Many studies suggest that the restoration and recovery of borrow pits and abandoned surface mines requires a sequenced order of restoration steps to efficiently recover these areas (Barton et al. 2006). Similarly, ecological recovery of heavily used military areas is likely to require efficient steps toward recovery.

Ecosystem restoration

Many questions exist relative to restoration and interpretation of success. For example, is restoration success better facilitated by establishment of small islands of high diversity with hopes of seed radiation from the restored units or is a better strategy to broadcast seed over large areas with expectations that most seed will not germinate, buts that those established individuals will result in a collapsed recovery of the system. If the former case is true, what pattern and distance between "restored islands" is most efficient for seed spread. Further, little information is known relative to which species need restoring and which species will recover with changing condition. Finally, the sequence of establishment remains in question; "should all desired species be planted together?," "should seed or juveniles be used, and for which species," "should species that support pollinators be established prior to matrix grass species," and various other establishment pattern, sequence, and technique questions exist. One major question that still remains to be answered is should the desired understory be established prior to longleaf pine planting, with longleaf pine planting, or can it be effectively established beneath mature open forest conditions. Several other questions exist, different strategies may be needed for different understory species or maybe the rhizosphere (e.g., mycchorhizae) needs to be amended and recovered prior to any plantings. Further, the role and reintroduction of fire in facilitating and accelerating system level restoration of human-impacted systems remains a research issue.

Most successful restoration understanding and actions have either been focused on one or a small suite of species (e.g., longleaf pine, wiregrass) or have been in areas with repressed habitats with sufficient biological integrity that did not require significant reintroduction of species and, beyond the reintroduction of burning, other regulating mechanisms (e.g., Eglin Air Force Base, Fort Bragg). Walker (1993) found that in most settings, either the matrix grass (wiregrass) is suppressed without supported savanna species or low densities of other savanna species are present without the matrix grass; thus, different strategies toward system recovery may be needed. Few success stories exist for areas that were once heavily used agricultural areas; and these areas may require an alternative strategy for rehabilitation and restoration.

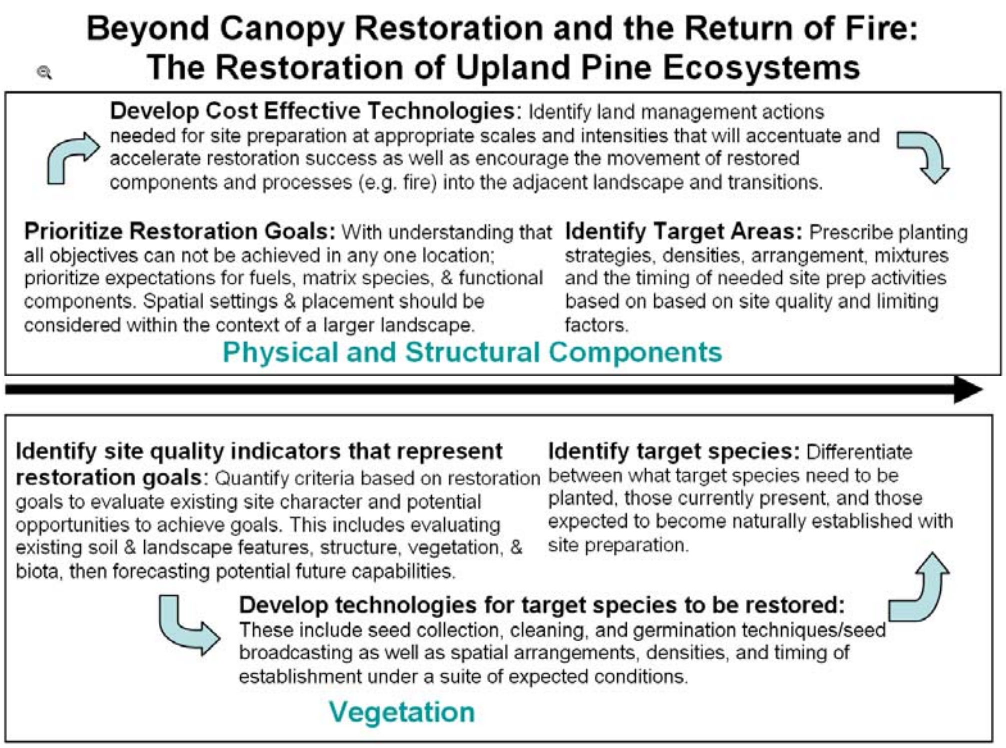

Figure 69. The restoration of upland pine ecosystems.

Though anchored in the theoretical debate of the “neutral” theory (Brown 2002) and various facilitation theories (Hubbell 2000), restoration science, with a few exceptions (Kirkman et al. 2005, Walker et al. 1993, and others), have focused very little on operational activities and sequences. Much of the research has focused on theoretical construct and the improvement of necessary seed collection, “gardening,” and out planting techniques (Glitzenstein & Brubaker 2002, Kirkman et al. 2004). Future research in the area of ecosystem restoration should continue to emphasize species understanding but graduate toward the identification of assembly and restoration strategies that mimic natural processes of community development.

The influence of intermediate or infrequent training-use patterns on forest development

The majority of the upland forested area at Fort Benning receives, or has received, some amount of mounted training. Typically, these areas are used in conjunction with training and deployment schedules. Thus, areas often have periods of high use followed by a period of limited use or recovery. Training associated with deployable units (e.g., third brigade) is advanced and results in complex, often intense disturbance patterns. In contrast, the training schools (armored training school, infantry school, etc.) generally have predictable patterns of repeated-use from week to week, month to month, and so on. Therefore, maintenance activities differ from area to area and with user group. As expected, the earlier SEMP studies found mechanized maneuvering to be associated with the highest disturbance risks; further, the most dominant and "at risk" landscape type are those areas that receive low to intermediate training.

Therefore a useful question for a moderately-used training compartment is "Does pattern of mechanized maneuvering (mounted training, forestry operations) in a forest influence spatial processes and outcomes; specifically, is it better to have scattered light disturbance throughout a forest or have higher intensity disturbance confined to a smaller area." Generally, training events are encouraged to maximize the use of the training landscape; thereby spreading the disturbance, emphasizing natural recovery, and reducing per acre cost. However, "best training practices" have not been defined relative to acceptable forest health, soil compaction, and acceptable patterning of fuels for burning and understory habitat. Further, yet to be determined is land-use condition and pattern facilitates the establishment of cogon grass, an aggressive invasive exotic that refines habitat conditions.

Relative to tree health, a commonly asked question is "Does frequent root-disturbing management actions influences tree survivorship." These management actions mostly include mechanized thinning and harvesting, but may also include the use of herbicides or disruptive military training. In infrequently burnt areas, offsite plantings, or over-stocked pine stands, this may include deleterious effects of fire reintroduction. Independent of pathogen-host habitat characteristics and direct effects on the host, using three features, eight potential pathogen scenarios or models can be developed to evaluate potential forest health issues: a) whether infection is dependent on in-place activation or pathogen immigration, b) the dependence on or lack of a secondary transfer host (e.g., beetle vector), and c) whether a minimum health threshold is needed to define health risk. Each of these combinations equates to potentially different forest health risks, responding management actions, and expected spread patterns. For many pathogens, frequent ground disturbance increases the opportunity for root disease establishment, and may favor inoculation and transport of fungal pathogens (Otrosina et al. 2002). If tree and forest health is a question of pathogen opportunity or limited tree tolerance, then some root damage to most trees (shifting path use) would result in greater tree health risk; thus, scattered disturbance may result in tree loss. Conversely, if tree and forest health are dependent on exceeding a tree tolerance and recovery thresholds, then concentrated training (repeated path use) would expose a different proportion of trees to health risk.

Patterns of surface soil disturbance influence the spatial complexity and recovery of soil characteristics and process dynamics. All of the earlier SEMP studies indicate that soil disturbance without compaction is a recoverable feature, particularly when associated with sandy surface soils. However, land-use pattern defines the frequency and intensity of soil disturbance, indirectly recoverability, which may lead to elevated soil compaction, soil movement, and prolonged disruption of processes that influence C and nutrient dynamics. Perhaps with a “worst first” mentality to soil remediation, it may be better at some scales to allow soil disturbance to be focused on specific paths, trails, and other locales. Further, observed soil disturbance may be a spatial and vertical aggregate of the collective condition at a larger scale. Hence, problems associated with compaction may, through physical processes, build and expand to adjacent areas. For example, the local initiation by the preferential accretion and build up of clays, organic matter, and cations from the surface to deeper layers can lead to expanded development of inert, spodic, lateric, or impervious fragipan sub-soils.

Habitat features, and the spatial distribution of resources that influence those features, influence species use. Evaluation of patterns associated with breeding bird populations are particularly useful because they are spatially agglomerative of the general condition at scales reflective of management and training activities and their life cycles allow them to be responsive from year to year to slight changes that may define or reflect other conditions within the habitat. Therefore, spatial continuity and range of condition is likely to influence the suitability for nest development. An earlier SEMP study found that bird composition reflects forest disturbance and condition (Sargent et al, 2003). Mid-story density and pattern are particularly reflective of conditions within an upland pine stand; other studies suggest higher breeding bird diversity with increasing canopy and midstory complexity and diversity, but lower density of indicator species such as Bachman's sparrow, Henslow's sparrow, pine warbler, and so on (Kilgo and Blake 2005).

Similarly, the distribution of mid-story influences fire behavior (Achtemeier et al 2005) and expected post-burn results. A commonly observed difficulty in burning areas with recent mechanized training is establishing a means for fire to move from localized areas that have little or no fuel into adjacent areas that have heavy fuels characterized by significant flashpoint energies (e.g., near continuous high density mid-story of the tardily-deciduous *Quercus hemisphaerica* and a moist, dense, sclerophyllous litter layer beneath). Therefore, the absence of "carrying fuels" reduces fire spread, allows for fuel "smoldering," and facilitates inefficient combustion, which collectively leads to air quality issues associated with prescribed burning (recent SERDP SON/RFP).

Collins et al. (2005) identify high frequencies of small-scale disturbance patterns within partially forested areas through out Fort Benning, these disturbances were particularly frequent in moderate military-use sites underlain with clayey soils. These data collectively indicate that clayey soils are slower to recover, which is consistent with findings from other SEMP studies (Garten 2005, Kryszik 2005, Reddy 2005). It should be noted that these disturbances were of derived from various training-use and legacy-use actions.

Mounted training maneuvers can involve various formations that are necessary to address a set of training objectives; these include linear columns, broadly scattered formations, etc.. Given a particular set of training needs and requirements either a fixed pattern of movement can be used, whereby the same "paths" are taken by individual vehicles with each repeated event. The alternative is to allow individual vehicles take uniquely defined paths, within the scope of the training objectives. The former scenario would result in less frequent, more disturbed paths with greater separation by undisturbed sections; the latter would result less intense disturbance that is distributed across a broader portion of the landscape. It should be obvious how differences in strategy toward training placement would have differential effects on tree health, due to differences in root disturbance and compaction, as well as habitat type and quality. Further, these differences would likely affect soil processes that influence resource availabilities and transfer of C and N within and through the ecosystem.

Tree health will be assessed using accepted forest health monitoring criteria (USFS, 2001), soil site quality will be assessed using the indicators identified by SEMP I projects (Dale 2006), and understory conditions will be assessed using nested vegetation plots that are imbedded within a grid of breeding bird census points. Bird census techniques will follow those guidelines recommended by the Audobon Society and Partners-In-Flight. Fuel characteristics will be captured using vegetation plots and will be focused on those parameters needed for the standard regional fuels model (BEHAVE) (USFS, 1999).

One aspect of land-use planning is to focus on optimization of sustainable use in which a wide variety of conditions can be considered sustainable. For example, concepts of sustainability relative to impact or DUD areas are quite different than those for heavy-traffic areas. Therefore, measures and concepts of uniquely defining criteria for site durability (resistance), site stability (volatility), site recoverability (capacitance, resilience), site flexibility (specificity, between-state elasticity, within-state malleability), collectively equate to site suitability (compatibility) are sometimes evaluated for practical use. However, in most settings, measures of sustainability are simply an educated estimate of the number of days between remediation or restoration events or sustainability is solely dependent on the level of disturbance resulting from the most recent training scenario. But, a better understanding of the physical and biological processes could lead to extended sustainability periods or elevated levels or training without the need for costly remediation and restoration.

Using Garten's 2005 nitrogen-limitation productivity model, the recovery time needed to return to either a sustainable open field or mature forest condition. The model considers existing conditions prior to disturbance and is functionally based on C and N pathways that allow for ecological recovery towards a sustainable steady-state condition. However, several relevant scientific questions remain and include:

1. Does size and shape matter? Does accelerated recovery occur along disturbance margins as opposed to interiors and do complex shapes and surfaces lead to more rapid recovery toward a desired, sustainable state or training land condition?
2. Is training land sustainability influenced by legacy conditions, and how is this relationship influenced by training intensity, duration, and frequency.
3. What role does soil "sealing" play in erosion risk (DeBano & Swank 2000), accelerated water runoff rates, sediment movement, and erosion risk and are the "crusts" that cause soil sealing solely due to biological activity or partially related to surface mineral crystallization through thermally accelerated redox processes.
4. Is "durability" and "recoverability" the same for different vegetation types? Does plant life form better reflect "durability" or "recoverability"? And do these patterns hold true for different soil types?
5. As productivity and capacity to recover decline and degrade during continued heavy-use, a series of "steps" are likely to be evident; therefore the questions are: (1) what are these ecological "steps" or sequences of conditional change that lead to decreased quality, (2) are these "steps" or sequences the same as those that occur as sites improve. In other words, do ecosystems degrade and aggrade in the same manner?

Environmental impacts and implications of repeated heavy training

Based on Dale (2005), Collins (2005), and many others, certain life forms and families are more sensitive to disturbance and better able to recover. Recovery can be in the form of plant replacement through germination or simply spreading and resprouting by damaged plants. Plant cover is critical to high-use areas because it lowers water energies and release rates by rainfall interception, it reduces unrestricted surface water movement that results in erosion, aerates and builds the soil, and, through shading, provides a less hostile soil surface microclimate. Therefore periodic assessment of the types and amounts of plants recovering in these heavy use areas because: (1) in some cases, they are suitable for planting in other highly disturbed areas, and (2) they provide a relative assessment of the progress of recovery as well as the durability of what remains. To meet this objective, sampling strategies used in bare land and desert assessments will be used. The focus will be to quantify limited coverage and determine if a life form relationship exists relative to those life forms extirpated and those renewed through seedling establishment.

The relationship between land-use and risk of surface and gully erosion is related to a series of training- and management-influenced risk factors. Mechanized traffic results in a) canopy loss, b) decreased ground cover and litter cover, and c) mineral soil disturbance. Each of these factors has independent effects as well as jointly congruent impacts.

As identified by Garten 2004 and the continued work of SI-1462 (Liu, personal com.), the state and condition of soil C and N budget define soil capacity and its ability to support different land-uses. Sustainability, as well as durability and flexibility, develops from a site's inherent capacity and functional efficiency in providing the necessary resources to support plant growth. Again, as with influencing surface erosion potential, organic material can be added to a severely disturbed site and slowly build soil capacity to support a wider range of land management and training expectations.

As depicted by Figure 70, mechanized equipment impacts the landscape and the potential for erosion through reducing the canopy, reducing forest floor coverage and litter, and disrupting the mineral soil. Canopy loss results from direct losses as well as indirect affects associated with root damage, reduced vigor, and reduced health. The implication of reduced canopy coverage is reduced shading, reduced water demand, reduced organic inputs to the soil, as well as reduced canopy interception of precipitation. Reduced shading, coupled with ground cover and litter cover loss, results in increased soil surface temperatures and evaporation potential. Both influence seed germination and seedling survivorship of natural and planted cover types. The loss of canopy cover also increases sediment detachment because of increased raindrop energies.

The loss of ground cover vegetation and litter influences microclimate conditions at the soil surface as well as percolation and aeration via root turnover patterns. Ground cover and litter volumes and types also influence soil processes such as mineralization. Finally, distribution patterns of surface vegetation and organic litter generates surface complexity and "roughness" that equates to resistance of kinetic forces associated with non-laminar flow and corrosive force. Therefore, water force velocities and the energy needed for sediment movement is significantly dissipated by "surface debris."

Mineral soil disturbance associated with mounted training or movement of mechanized equipment has two general influences on soil characteristics; compaction and loss of surface soil structure. Compaction directly effects sub-soil characteristics associated with drainage and sub-surface water flow. Altered soil surface structure has a variety of influences such as infiltration rate, clay migration, the redistribution and loss of organic material, as well as resource (nutrients, water) holding capacity and process dynamics. Clay migration results in partial redistribution to the compaction zone; hence, further reducing infiltration through the sub-soil.

The formation of biological crusts occurs in highly disturbed, exposed soil areas and is facilitated by a) reduced soil structure and b) altered C:N:P balances, both via mineral soil disturbance, c) the loss of ground cover and litter cover, and d) increased soil temperatures via the loss of canopy shade. Even temporary biological or mineral crusts are of concern because of the high amount of rainfall annually and with each storm event.

Interaction between terrestrial land-use and watershed inputs that effect water quality conditions

The adaptation and implementation of the BASINS model (SI-1467) will address the relationship between collective land-use and stream and water quality dynamics. This research is, in part, being driven by water quality concerns at the installation scale as well as those features associated with specific segments of stream. Also, SEMP and SERDP findings indicate that (Dale 2006, Mulholland 2006) stream and water quality are cumulatively derived conditions that are strongly tied to the watershed catchment use. Stream conditions that influence the biota are strongly tied to water quality, particularly water quality associated with storm events. Road density and the percentage of bare ground w/in the watershed are of particular importance. An apparent threshold is exceeded when more than 15% of the watershed catchment area is bare ground (Dale 2006, Mulholland 2006). In fact, these influences are significant enough that normally conserved nutrients (NO3-, H2PO4-) have elevated base flow and storm flow concentrations. These patterns could be due to a) a decline in stream ecosystem function and efficiency (caused by sedimentation and stream bed instability), b) increased sediment loading is sufficient enough to elevate concentrations through bulk transport, c) an increase in terrestrial input thereby exceeding the capacity and demand for these nutrients within the transition forest, or d) because of declining forest health, a loss of root uptake efficiency and demand for these nutrients within the transition forest.

Given these relationships, our focus is to address the latter two possibilities and determine if transition forest health influences these relationships. It should be noted that a current SERDP funded project through ORNL (SI-1452), is addressing the first two possible alternatives. Specifically, are unhealthy forest transitions less capable of sediment and chemical storage and stabilization; if so can it be improved through BMP expansion or low-cost understory restoration? Jolley and Lockaby (2007) found that low levels of sediment input result in lost root health, declined tree growth, and projected declines in canopy tree survivorship.

Preventative measures, as well as remediation and stabilization efforts, to slow sediment transport from upland to wetland positions can be costly. What is important is to determine when these transitions begin to loose capacitance and efficiency of slowing nutrient and bulk soil transport (gully formation). Therefore, passive management via the natural capacity of the system to slow and endure sediment input is an appropriate option when limited funds are available. These concepts pose a series of scientific questions related to Fort Benning land-use and other ongoing studies:

- Determine nutrient storage and transfer rates in soluble and bound forms and its relationship with stream concentrations and bed sediment stability. This objective includes estimating transport rates of surface and sub-soil sediments.
- Determine if higher levels of disturbance result in increased canopy tree mortality and a loss of precipitation interception capacity.
- Evaluate the likelihood of invasion by exotic species into frequently disturbed sites. This includes evaluating transition sites that receive sediment input from adjacent areas with regular or episodic training.
- Determine if restoration of native vegetation or expansion of BMP's rapidly mitigate the above relationships.

Upland transition and wetland habitats chemically filter and stabilize sediments associated with upland land-use disturbance. To improve water quality associated with non-point source pollution and sedimentation, state recommended Best Management Practices (BMP) were set in place to provide a buffer between various upland land-uses and surface water. Several studies have evaluated the effectiveness and limitations of these BMP buffers; however, few have looked at differential effectiveness of buffer types or the impact of ecosystem health on the buffer effectiveness.

If different buffer types and transitions have differential effects on chemical and physical transfer of terrestrial sources to into and through the wetlands, then some management opportunity may exist to maximize the effectiveness of buffers. Ecological processes associated with differential species affects and dynamics could potentially be facilitated through selective removal of less preferred species and planting replacement with more desired species (e.g., less sediment-sensitivity, greater chemical storage capacity).

- Does forest stress (as indicated by mortality and growth differences) caused by sedimentation reduce efficiency in nutrient capture (NO3, PO4),
- Accelerate surface sediment movement, or,
- Increase the frequency and advancement of gully erosion.

In some areas, transition slopes and wetlands are at risk of periodic sedimentation from the upland areas. Jolley and Lockaby 2007 found that even small amounts of sedimentation resulted in increased fine root loss, a reallocation of C resources for root replacement, and reduced health and vigor of shrubs & trees that have been subjected to sedimentation. Essentially, the collective decline of woody plant health and burial of ground cover layers results in a loss of efficiency in chemical uptake, loss of resistance to continued sediment movement, and a loss of resilience to recover from sediment deposition. From the stand point of ecosystem services, this may suggest that to achieve comparable benefits from riparian buffers, greater area would be needed to “produce” similar levels of water quality.

- Are stressed habitats subject to more rapid invasion by invasive species (e.g., Chinese privet), and,
- How does the establishment of these species affect the efficiency of ecological services of transition habitat, and,
- How does the establishment of these species change habitat conditions and constraints that selectively support other species and “contributed value” from habitat connectivity?

Once established, these species often become defacto “foundation” species that redefine resource cycles, habitat conditions, and disturbance regimes. If non-native species are found to be more invasive along these sediment-stressed corridors, then proactive focus can be made to remove them from the general area.

Advancing qualitative expectations to quantitative assessment of Desired Future Conditions

SEMP-I chose to implement the 1997 SERDP ecosystem management workshop recommendations via projects to characterize the extant ecosystems at Fort Benning and define indicators of condition and discover those that could define thresholds in ecosystem condition. The program theme did not focus on providing tools for use by resource managers on the installation nor were these studies intended to address compliance and regulatory concerns. While this might now be considered a deficiency, it simply was not a goal at that time. The integration project by Dale, et al (2005) approached both the indicator projects results and the land management context from the perspective of a premise that indicators can be related to land management so as to be useful in making judgments about ecosystem damages from military training.

Dale et al. (2006) recommended a set of indicators and demonstrated statistical relationships among the indicators and land management classes (LMC's) The LMC's included many management factors of interest. This impressive body of work is made uncertain as a predictive and management tool basically because it deals with the integrated consequences of an unknown history (in any precise sense) of unmanaged and managed actions on the land surface or watersheds. This is complicated by residual impacts from legacy land use. Legacy complications apply to both the upland longleaf pine (LLP) ecosystems as well as the sloped and riparian systems. For example, Olsen et al (2006) note that highly impacted patches within the landscape have persisted for many years with little signs of recovery. Deposited sediments in riparian zones and stream channels appear to be related to row crop agriculture as the pre-military land use; this is still under investigation. To elaborate on this difficulty in indicators, consider the forest habitat conceptual model below.

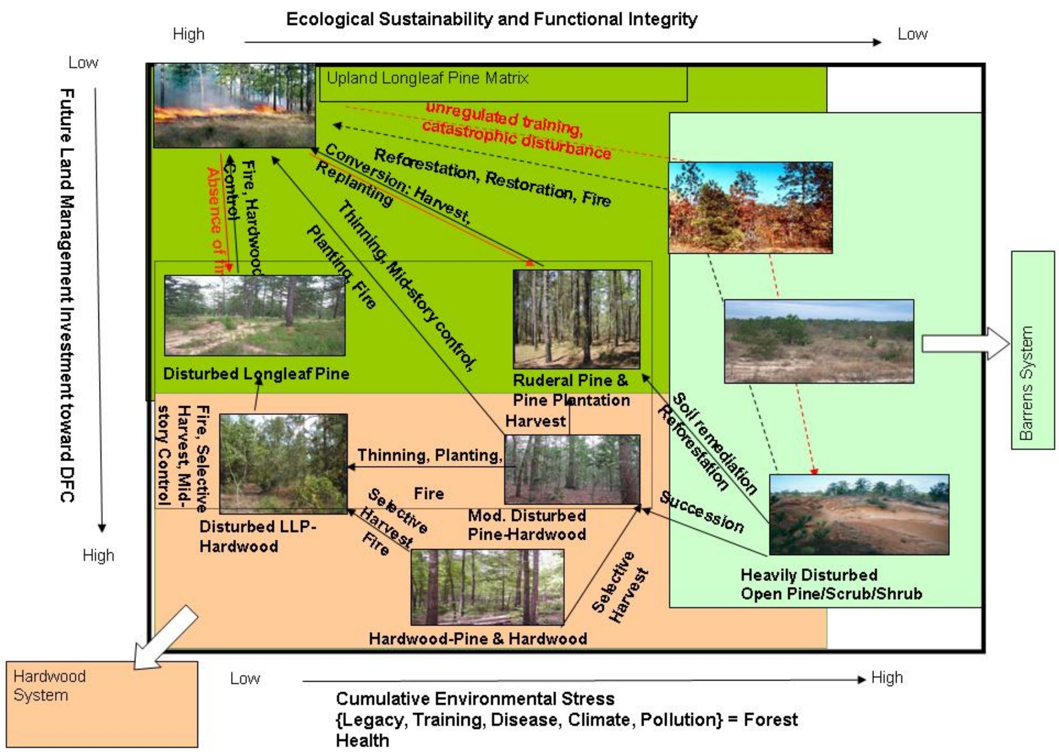

Figure 70. forest habitat conceptual model.

The management challenge for the use of indicators *per se* is readily seen. The pathways noted in the model above represent many of the current trajectories believed to move any particular site condition to the DFC matrix in the upper left corner. (Not all sites are intended to follow this pathway however) The INRMP and the related management investments are keyed to this model, tempered with expert opinion and on-site practicalities. In addition to these issues, successful restoration efforts require such techniques and technologies. In fact, these needs extend beyond the restoration (passive, active) of the longleaf pine matrix and should include other restoration efforts such as wetland mitigation banking, river restoration and stabilization, etc.

Indicators exist that characterize the conditions in each of the boxes (pictures) as well as the DFC case, which represents the RCW matrix or desired future habitat. In many cases the body of evidence showing that the steps shown are correct and necessary is impressive. Prescribed fire as a means to control under story and regenerate LLP is solid. Indicators as developed do not indicate the rate of likely restoration, do not diagnose difficulties in the pathways, and do not signal limitations to achieving success, nor do they offer insights into remedies or active management possibilities. To be sure, indicators can be used to confirm the set of conditions for any specific circumstance. In this sense indicators remain useful if not necessary as a means to track progress toward desired outcomes.

The existing and developing models are relevant to land management initiatives because they can be used to give prioritized, but unbiased assignments of necessary management actions. Currently, the landscape is managed using a defacto minimum threshold concept whereby management actions are only implemented when an observed minimum acceptable threshold is exceeded (e.g., too much mid-story beneath a pine overstory). These models will allow for a potential shift in focus toward optimizing the amount of area above a maximum threshold. Focus on minimum thresholds has been a long standing management approach (RCW habitat, water quality, etc.), many risk analyses suggest that greater emphasis should be placed on expanding and maintaining the proportion of “achieved” conditions as opposed to taking a “worst first” approach. Generally, the “worst first” approach is costly and inefficient because repeated efforts are needed to achieve long term progress. Once developed, these models (particularly Bayesian structures) will allow for a user-defined balance of management priorities. Further, type I and type II error relationships can be more effectively balanced to represent the desired risk-reward relationship. For example, emphasis of RCW recovery initiatives seems more focused on avoiding failure (non-compliance) than achieving long-term success.

Part II: Additional SEMP Projects

7 Examination of Sedimentation in Riparian Areas at Fort Benning

Military Installation, Georgia
Project Report – August 13, 2008
B.G. Lockaby, Principal Investigator

Introduction

Although sediment is listed as the most common non-point source (NPS) pollutant of surface waters in the United States (http://www.epa.gov/owow/nps/facts/point1.htm), we lack a clear understanding of sediment dynamics within watersheds. Specifically, we do not understand the influence of legacy sediment accumulation on total suspended solid (TSS) concentrations and loads in streams. The need for this information is particularly acute in the southeastern United States where agricultural land abuse in the 19th and early 20th centuries caused major erosion from uplands and subsequent deposition in riparian corridors (Trimble 1974). This period, known as the cotton era, was characterized by failure to incorporate conservation practices into farming activities (Lockaby 2008). Trimble (1974) estimates that the total erosion was sufficient to have lowered the entire Piedmont physiographic region by 10 - 30 cm.

It is clear that much of the sediment lost during the cotton era was deposited in lower topographic positions (Lockaby 2008). In the Piedmont of Georgia, Jackson et al. (2005) estimated that approximately 1.6 m of sediment from historic cotton farming had been deposited atop the original or antecedent floodplain of Murder Creek. This depth equated to erosion losses of 12.2 cm of topsoil across the entire watershed. In higher order streams such as the Roanoke River within North Carolina, deposition of historic sediments may have been much greater and is estimated at 6 m in some locations (Dr. Cliff Hupp, USGS - personal communication). Consequently, many streams in the eastern United States have undergone morphological changes in terms of burial of surrounding wetlands and a prevalence of incised channels with unstable streambanks (Walter and Merritts 2008, Jackson et al. 2005).

These sediment deposits also occur within stream channels and may be exported over time as contributions to the total sediment loads of streams and rivers. In Murder Creek, 22-35% of the suspended sediment load was thought to be associated with the bedload (Jackson et al. 2005). The potential for legacy bedloads to contribute to total stream loads has raised questions regarding whether land use activities are solely to blame for elevated concentrations (Smith 2006). This is a critical issue to land managers who may be cited by regulatory agencies for degradation of water quality.

The issue is not confined to the Southeast and currently is a major source of debate in connection with the Chesapeake Bay. In that region, as in the Southeast, the relationship of legacy sediment to water quality is unclear and Smith (2006) refers to the issue as the ‘culprit or scapegoat’ debate. Although the degree of stability associated with legacy sediment is not well understood in many locations, the issue is deemed sufficiently important by the Pennsylvania legislature to provide funds for conservation measures including legacy sediment remediation (PA Resource Protection and Management Act, 2007, Article XVII-E).

Clarification of the role of legacy sediments is a particularly critical issue at Fort Benning, Georgia where the landscape was highly disturbed during the cotton era and remained so after acquisition by the military in 1918. There is clear evidence of historic farming activity including the presence of old water wheels, remnants of small bridges and abandoned, farm road embankments. Although a detailed timeline regarding land use is unavailable for the location, there have been determinations that the landscape was 97% forested in 1827 based on survey records (L.M. Olsen, V.H. Dale, and T. Foster, unpublished report to SERDP) but was highly disturbed in 1944 (Maloney et al. 2008). Unfortunately, the 1827 and 1944 temporal snapshots represent pre- and post cotton era information but provide no insights on the extent of agriculture from 1830-1920.

To that end, our objectives were to examine the following aspects of the legacy sediment question at Fort Benning:

1. the depth of historic sediment on the floodplains of Bonham Creek and Sally Branch.
2. recent (since 1964) sedimentation rates and sources using ^{137}Ce isotope analysis.
3. recent (last 2-3 decades) sedimentation rates using a dendrogeomorphic approach.

4. current export near new stream crossings on both streams.
5. amounts of historic sediment within stream beds.

Study area

Fort Benning straddles the fall line or the line of demarcation between the Piedmont and Coastal Plain physiographic regions in Georgia. Both Bonham Creek and Sally Branch are situated in the upper coastal plain in close proximity to the fall line. These are 4th order streams and portions of both watersheds lie within the newly constructed Digital Multipurpose and Practice Range Complex (DMPRC). The area of the Bonham Creek watershed is approximately 1270 ha and that of Sally Branch is 2530 ha while the respective slopes are 5.04 and 5.45 % (Bhat et al. 2006). Floodplain areas are 62 and 106 ha respectively.

The riparian zones are forested primarily with sweetgum (*Liquidamber styraciflua*), water oak (*Quercus nigra*), red maple (*Acer rubrum*), yellow poplar (*Liriodendron tulipifera*), and loblolly pine (*Pinus taeda*). Soils include the Bibb (Typic fluvaquent) and the Chastain series (Fluvaquentic endoaquept) (Lockaby et al. 2005). Several newly constructed, dirt roads cross each stream and seasonal precipitation was less than the 30 yr average during much of 2007 (Figure 71)

Methods

All sampling occurred from the summer of 2007 through summer, 2008 except for that associated with the sediment pins. The latter measurements began in January, 2007.

Soil cores – Sampling occurred in a grid pattern consisting of transects oriented perpendicular to the main axis of each stream. Transects were 50 m apart and extended from stream banks to uplands, a distance that ranged from 10 - 100 m. Along each transect, plots for core and dendrogeomorphic sampling were established at 10 m intervals (Figure 72).

Soil cores were extracted using an auger to 1.5 – 2.0 m depths which coincided with the occurrence of abrupt changes in texture and color from sandy clay to sand and dark gray to white respectively. At the juncture of the dark gray clayey and white sandy layers, dead tree roots, portions of residual stumps, and logs were sometimes visible (stumps and logs protruding from stream banks) . Due to the aquic nature of the soils, the portion of the soil profile from an upper depth of approximately 30-45 cm and extending down into the sand was reduced and saturated continuously. In addition, profiles along stream banks were often used to estimate depths to the sandy layer and, when possible, cores were taken within the stream beds in order to estimate depths of historic sediment there (i.e., depth of bed load). The morphology of the sandy layer at depth along Bonham Creek and Sally Branch was similar to the description provided by Jackson et al. (2005) of the original floodplain surface at Murder Creek.

A total of 168 cores were collected, i.e., 118 from Bonham and 50 from Sally. Each core was divided into 30 cm intervals and subsampled for the following: color, texture, number of protruding live and dead roots, and bulk density. Also, relative elevations were recorded for all plots and within stream channels.

Elevations - Elevations were measured at each sampling point on both floodplains using a level and standard telescoping rod. For each section, all transect plots were surveyed to allow comparisons both between and among transect plots. Also, where transects intercepted streams, the relative elevations of the stream banks and bottom (mid-point across the creek) were surveyed.

Using ground elevations, topographic cross-sections were prepared for each stream transect. We then used the soil core depths to the original surface for each corresponding plot to prepare a historical topography relative to current conditions. Cross-sections were plotted for each transect and examined for trends related to stream beds. This approach allowed estimation of the depth of residual cotton era alluvium within channels.

Dendrogeomorphic sampling - On each plot, a maximum of three small trees (3-30 cm at the root collar) were sampled according to the procedure outlined in Hupp and Morris (1990). This consisted of severing the tree at the root collar and at the soil surface (the soil surface being above the root collar if sediment deposition was occurring and below if scouring or export dominated). The difference in age between the two points was ascertained and the distance above or below the root collar was expressed as an annual rate of sediment import or export respectively. A total of 367 trees were felled, i.e., 248 on Bonham Creek and 119 along Sally Branch.

^{137}Cesium atmospheric fallout fingerprint – Dr. Jerry Ritchie with the USDA Hydrology and Remote Sensing Laboratory in Beltsville, MD conducted the preliminary evaluations of sediment accretion and sources at Fort Benning using Cs-137 methods. Dr. Ritchie has extensive experience analyzing Cs-137 activity as a marker for soil accretion and movement. These methods rely on the detection of ^{137}Cs, a radionuclide that was transmitted worldwide as a result of atomic bomb testing. Because ^{137}Cs readily adsorbs to sediment particles it has become a very useful marker/tracer for examination of sediment movement (Ritchie and McHenry 1990, Brigham et al. 2001). Sediment accretion in the Bonham Creek and Sally Branch floodplains was evaluated by collecting 35-cm soil cores (one per floodplain) which were divided into 5-cm increments. The analysis of sediment accretion and sources were conducted using Cs-137 methods starting in September 2007. For each core, soil increments were individually bagged in a freezer bag and labeled for transport to Auburn University. At Auburn, all samples were oven dried, crushed, and sieved to 2-mm. Samples were then shipped to Dr. Ritchie's facility in Beltsville for analysis of ^{137}Cs activity. Gamma-ray analyses were made at the U.S. Department of Agriculture's Agricultural Research Service Hydrology Lab in Beltsville, using the Canberra-2000 Genie-2000 Spectroscopy System to quantify ^{137}Cs activity (Bq kg^{-1}) in each sample.

To estimate floodplain soil accretion, maximum ^{137}Cs soil activity among each of the soil core increments was identified and the maximum ^{137}Cs activity was linked to the maximum exposure year of 1964 (year of maximum worldwide atomic bomb testing). A rate of accretion was calculated based on the depth of soil above the increment. For sediment sourcing, the collected sediment material and potential sources were analyzed for ^{137}Cs as described above. To quantify the relative contribution of each source to sediment in the creek, a simple mixing model was employed (see Nagle and Ritchie 2006 for details). It was understood that because of the limited scope of this work, all results were considered preliminary and may change with increased sampling.

Sediments were also collected from bedload material in the upper and lower reaches of Bonham Creek and Sally Branch. In addition, several soil samples were collected from potential sediment sources in the watershed including upland areas surrounding the floodplain, the floodplain, roadsides leading to creek crossings, and stream bank soil material. Each of these samples was treated as previously described.

Sediment pins – Whereas cores, dendrogeomorphic samples, and ^{137}Cesium fingerprinting were used to estimate longer term sedimentation, pins were installed to estimate current rates. Metal washers were welded to midpoints of 1m long, steel welding rods. These were deployed in a grid pattern at each of 7 road crossings on either Bonham Creek or Sally Branch. Rods were inserted into the soil until the washer was level with the soil surface and changes in distances from the soil surface to the washer were recorded monthly. A total of 330 rods were placed along stream banks at the crossings.

Results

Cores -The depth of the legacy alluvium averaged 176 cm and 172 cm on Bonham Creek and Sally Branch respectively. The overall mean of 174 cm is very close to the 1.6 m depth observed by Jackson et al. (2005) on Murder Creek in Georgia. There were no statistical differences among reaches or sides (east vs. west) of floodplains in terms of depth.

The depths and bulk densities recorded for the soil cores translate to a legacy sediment mass estimate of 2.3 t/m^2 on both Bonham Creek and Sally Branch. Expanded to a floodplain basis, we estimate that approximately 1.4 M and 2.4 M t of sediment accumulated on the Bonham and Sally floodplains respectively during the cotton era. These amounts equate to respective losses of 9.2 and 7.5 cm of topsoil across the watersheds of Bonham Creek and Sally Branch. Our estimates coincide closely with those of Jackson et al. (2005) for Murder Creek and Trimble (1974) for the entire Piedmont.

Elevations - In Bonham Creek, channel depths and their proximity to the original layer increased with distance downstream. In the highest reach measured, stream beds averaged 0.55 m above the original layer although the stream bed eventually intercepts the original surface further downstream (Figure 73). Although only one transect was sampled along the lower reach of Bonham Creek, it was apparent that channel depths were substantially deeper (averaging 1.83 m) than in upper reaches (1.16 m).

Based on existing and antecedent elevations, it was apparent that Sally Branch was more deeply incised into the alluvium than Bonham Creek (Figure 74). Using channel depth measurements (average top-of-bank to creek bottom), Bonham Creek had a significantly lower mean (±SE) creek channel depth (1.36 ±0.12 m) compared to Sally Branch (2.23 ±0.09 m)

(P<0.05). Because of the deeper incision along Sally Branch, transects were more likely to intercept the estimated antecedent surface compared to Bonham Creek. Of the nine Sally Branch transects where adequate topographic data were available, all had stream bottom elevations that were below the original surface layer. This contrasts with only two (or 17%) of the transects analyzed for Bonham Creek.

Dendrogeomorphic sampling – The average time period over which sedimentation rates were estimated (i.e., average difference in age between stems at root collars vs. soil surfaces) was 18 years. Rate estimates averaged -0.06 cm/yr on Bonham Creek and 0.01 cm /yr on Sally Branch. These rates are negligible and, although there is noticeable variation in scouring and deposition patterns at a microsite scale level, suggest that the surfaces of both floodplains have been stable over the last two decades.

^{137}Cesium fallout – Cs-137 data indicated that sediment deposition had occurred in both the Bonham Creek and Sally Branch floodplains since 1964. However, results may have been skewed since only one core per floodplain was collected and collection locations lay within 15 m of road crossings along each stream. Given the spatial variation noted in the dendrogeomorphic sampling combined with observations of greater deposition in the vicinity of road crossings, we discount the deposition suggested by the cesium data.

It appears that suspended sediments in both streams are most likely derived from in- channel sources as opposed to overland flow from uplands. Activity of ^{137}Cs in bedload material ranged from 0.00 to 1.46 Bq kg^{-1} in Bonham Creek and 0.00 to 1.70 Bq kg^{-1} in Sally Branch. Upland areas tended to have the highest ^{137}Cs activity ranging from 7.40 to18.15 Bq kg^{-1} in both watersheds. The closest ranges to those measured for the stream bedloads were from in-channel sources and possibly roadway sources.

Sediment pins – The pin sampling was designed to estimate accumulation or loss of sediment around each pin. Much of the period over which pin data were recorded was abnormally dry (Figure 71). Consequently, sediment movement over this time frame was likely less than what might have occurred in a period with average rainfall. During construction of crossings on Sally Branch, some sets of pins were destroyed by construction activity such as applications of large rock for stabilization of banks as well as excavation. Consequently, the Sally Branch sediment pin data are less comprehensive than the Bonham counterpart.

The period immediately after pin installation coincided with active construction of road crossings in the DMPRC and, as a result, there were soil losses of 1 – 6 cm at Bonham and Sally crossings between January – April, 2007 (Figure 75). Afterward, soil surfaces around pins either remained stable or exhibited some aggradation. Over the entire sampling period, sediment mass export averaged 216 kg/m^2 along Bonham Creek crossings. This is equivalent to 2160 t/ha and represents a considerable input of sediment to that stream.

Summary

It is apparent that the Bonham Creek and Sally Branch floodplains and stream channels have undergone very large volumes of sediment deposition and that original floodplain surfaces and stream bottoms were completely buried by that sediment. We estimate that 1.4 and 2.4 M t of sediment remain atop the historic floodplain surfaces of Bonham Creek and Sally Branch respectively. This amount and depth of sediment as well as the morphology of buried soil horizons are consistent with reports of widespread cotton era (1830-1920) erosion and deposition in the Piedmont physiographic region. This magnitude of erosion (approximately 8.3 cm across the two watersheds) and deposition would have caused major changes in the ecology of uplands, floodplains, and streams within the Bonham and Sally catchments.

The two watersheds present an interesting contrast in terms of sediment export and rate of return to pre-farming channel morphology. The Sally Branch watershed is larger and has slightly greater slope compared to the Bonham Creek watershed and, as a result, stream discharge and velocity may be somewhat higher in the former system. The greater amount of stream flow in Sally Branch has been sufficient to evacuate the agricultural alluvium from the channel to a much greater extent than has occurred in the Bonham channel. Consequently, the hydrological contrasts between the two watersheds are clearly reflected in different rates of recovery from cotton era impacts.

The data presented here demonstrate both the magnitude and longevity of sedimentation impacts on floodplains and streams near the Georgia Piedmont. However, many questions remain regarding the dynamics of sediment stability and transport as well as implications for natural systems and current water quality issues. Consequently, the results of this study may guide additional inquiry toward a more complete appreciation of the influence of legacy sediment on current land management issues.

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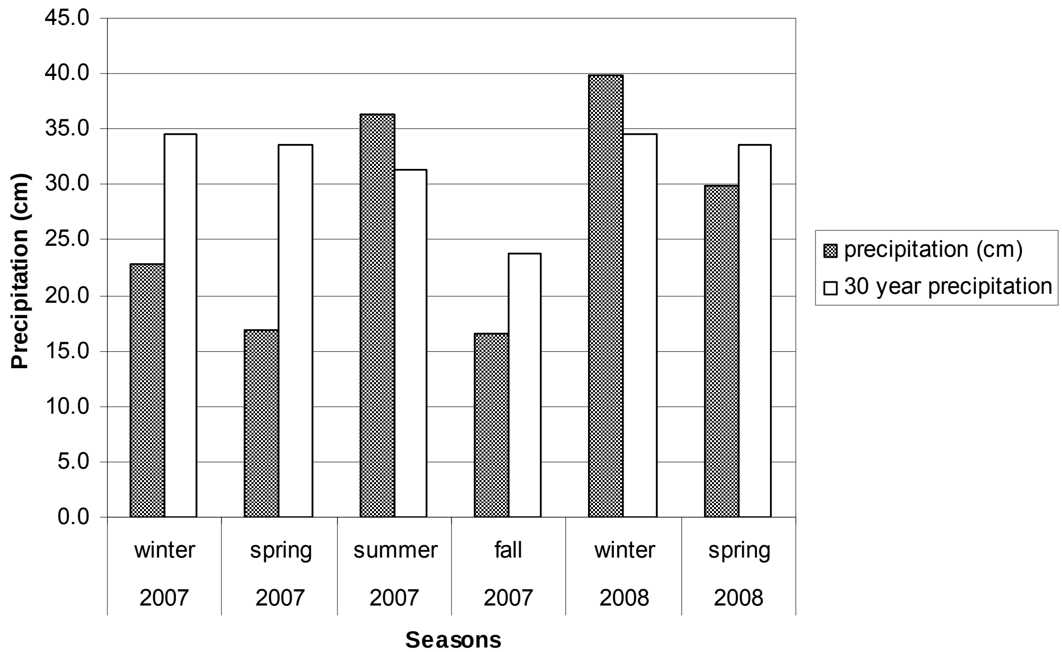

Figure 71. Monthly precipitation during study period compared to 30 year average precipitation.

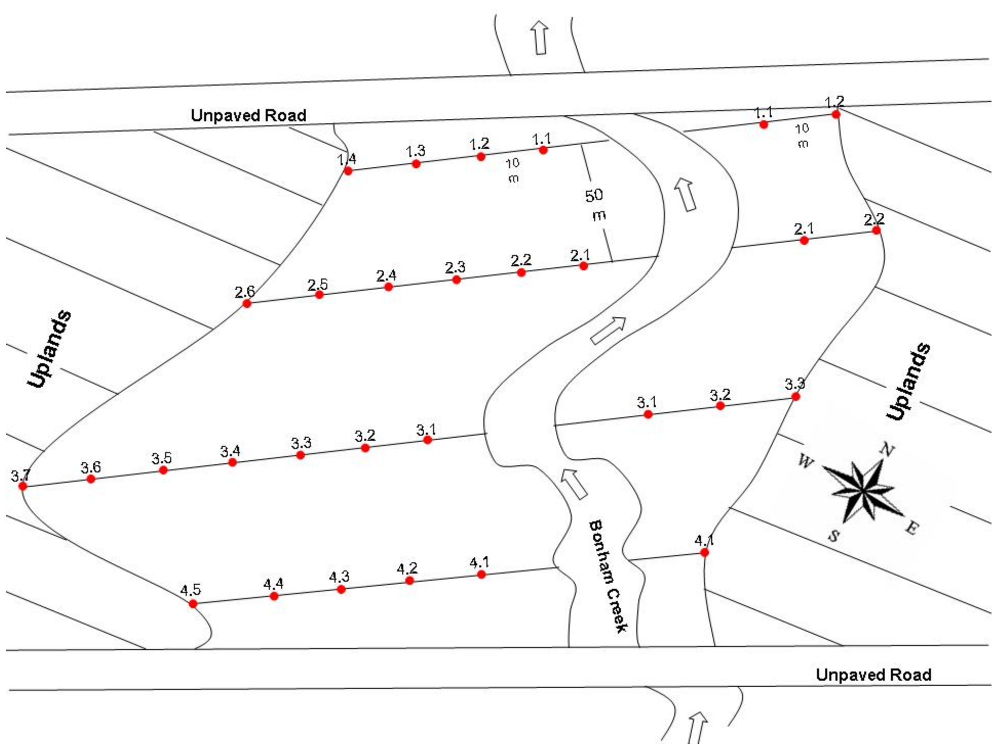

Figure 72. Generalized diagram of sampling transects and plots on floodplains of Bonham Creek and Sally Branch.

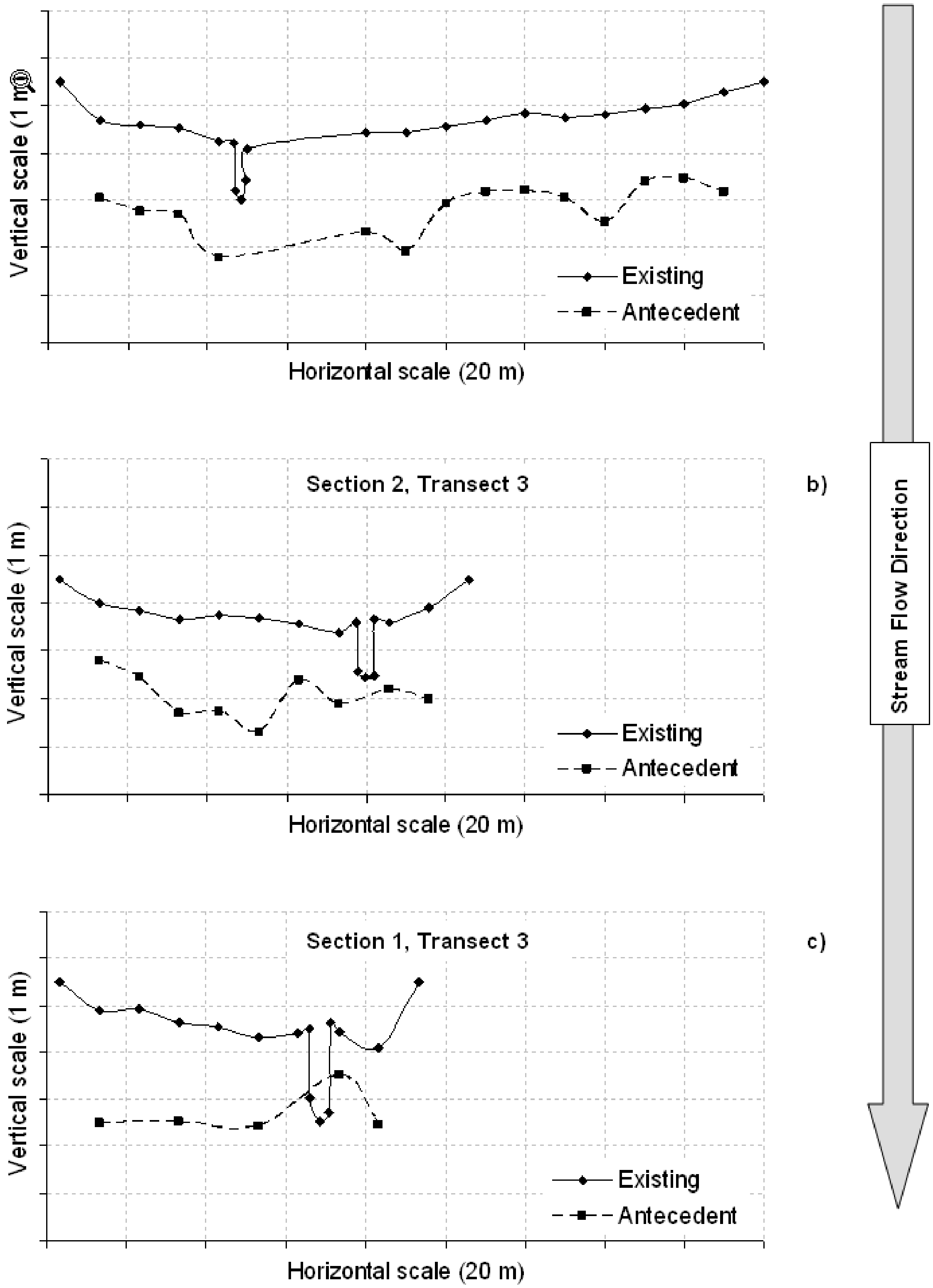

Figure 73. Current and antecedent elevations for representative transect along Bonham Creek.

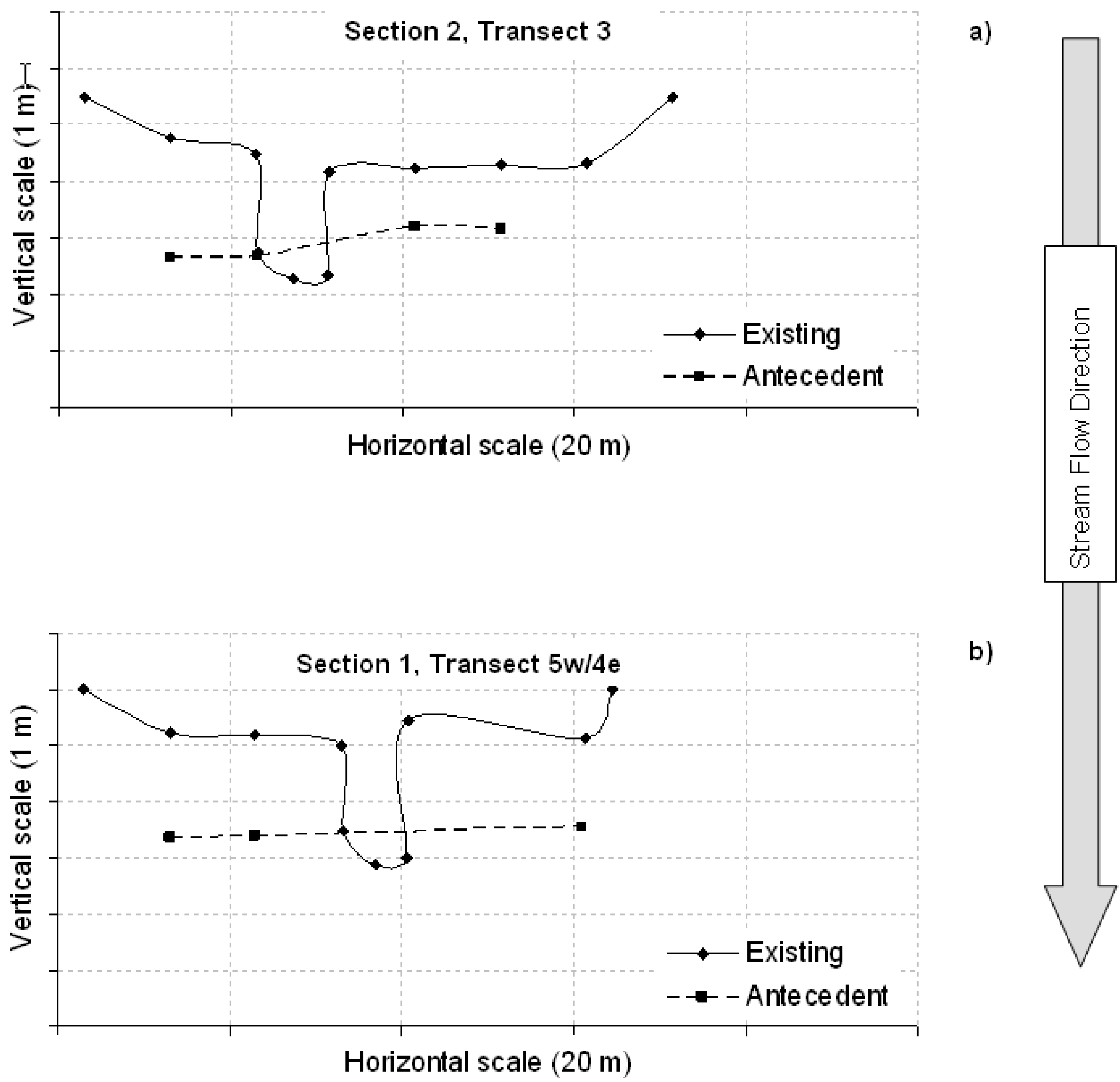

Figure 74. Current and antecedent elevations for representative transect along Sally Branch.

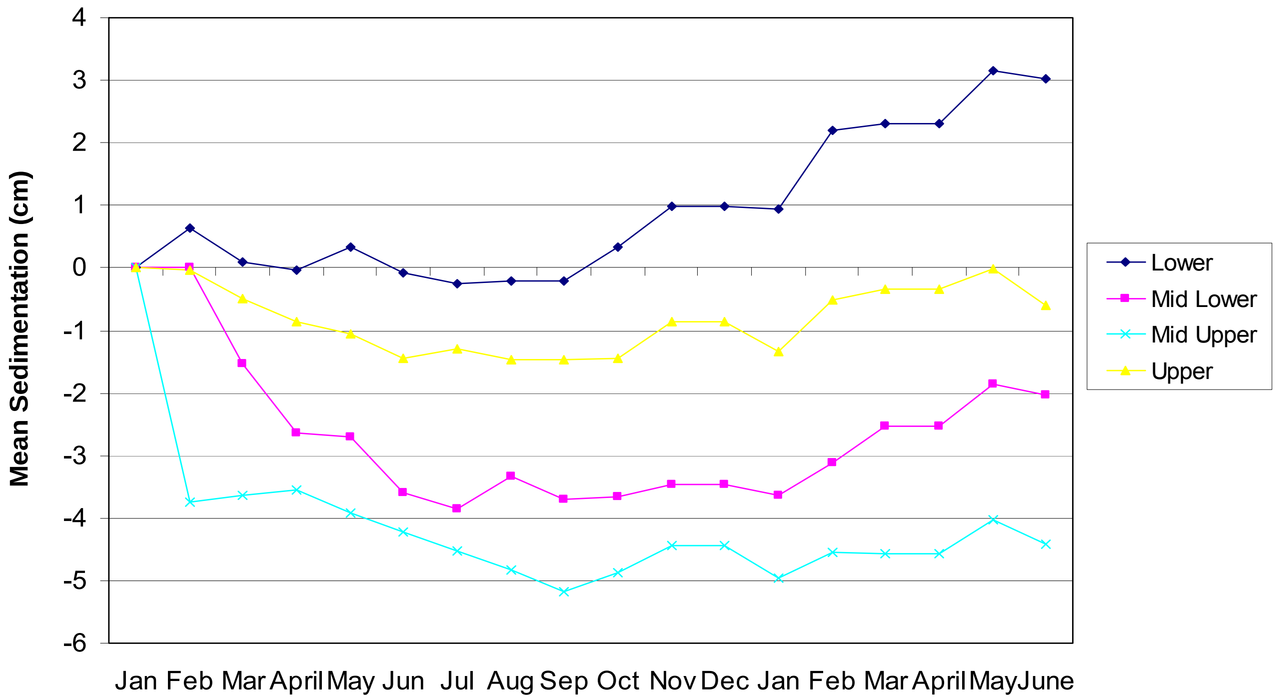

Figure 75. Monthly average depth of sediment near pins at road crossings along Bonham Creek.

SERDP Ecosystem Characterization and Monitoring Assessment and State of Land and Water Resources (David Price, ERDC-EL, Vickburg, MS)

Background

The Strategic Environmental Research and Development Program (SERDP), Ecosystem Management Project (SEMP), Ecosystem Characterization and Monitoring Initiative (ECMI), http://www.denix.osd.mil/denix/Public/Library/SEMP/semp.html, is a long-term, multi-agency monitoring initiative at Fort Benning, GA, to characterize the environment in and around Fort Benning and provide long-term databases documenting several environmental (meteorological, hydrological, biological and land cover) conditions in the ecosystem.* This monitoring program was designed to continue for at least 10 years and be a prototype for long-term monitoring programs at other military installations.

Purpose

The purpose of this report is to provide an assessment of the ECMI and the state of, or a benchmark of the land and water resources of Fort Benning, including the local and regional meteorological conditions. For a full description of ECMI, refer to Kress, 2001†.

Meteorology

Throughout the monitoring period from August, 1999 through 2007 there were several lessons learned concerning hardware selection, installation and implementation as well as equipment performance. For a full description see Leese, 2005. Overall, the meteorological stations performed near flawlessly through 2006, however the life expectancy of the sensors and equipment now requires that the meteorological stations be updated. Following are summaries of three studies completed in 2007 using the mete-

* Hahn, C.D., and Leese, D.L. (2002). "Automated Environmental Data Collection at Fort Benning, Georgia, from May 1999 to July 2001," ERDC TR-02-3, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

† : Kress, M. R. (2001). "Long-Term Monitoring Program, Fort Benning, GA; Ecosystem Characterization and Monitoring Initiative, Version 2.1," ERDC/EL TR-01-15, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

orological data set from 1999 through 2006 to evaluate the utility of the meteorological data as a factor in assessing the state of Fort Benning (Appendix C, White paper reports C4 and C5 by Dr. Dale Magoun) and one study to assess the potential applications of MET data and recommendations for the MET station network on Fort Benning (White paper C2 by Dr. Donald W. Imm).

Study one

The purpose and scope of the first study was to describe the meteorological (MET) relationship of weather data as measured at the ten (10) strategically placed MET stations at Fort Benning, GA and the National Climate Data Center (NCDC) controlled weather station located on the premises of the Columbus, GA airport. The MET of daily precipitation and temperatures were the two parameters under consideration and this study provides a historical depiction of these parameters and the interrelationships that exists. (For details see Appendix C, white Paper C4, by Dr. Magoun)

The correlation analysis performed indicated that the meteorological readings observed at the Columbus Metropolitan Airport could be used to predict with good accuracy the meteorological parameters of minimum air temperature and maximum air temperatures. The correlation coefficients between the sites of Columbus Airport and the U.S. Army installation at Fort Benning were 0.9701 and 0.9835, respectively, for the air temperature parameters. However, for the meteorological parameter of daily precipitation, the correlation coefficient between to the two sites was 0.6724. Although this coefficient was not as strong as the association with the air temperature parameters, it is sufficiently different from zero and does indicate that daily precipitation at Columbus Airport may be used as a predictor of daily precipitation at Fort Benning. The linear models which best describes these relations are given below in Table 29.

Table 29. Linear Predictors

Parameter	R-Square	Linear Model
Minimum Air Temperature (degrees F)	94.1%	$MinAT_{FB} = -0.388 + 0.9747\ MinAT_{CMAP}$
Maximum Air Temperature (Degrees F)	96.7%	$MaxAT_{FB} = 3.798 + 0.9497\ MaxAT_{CMAP}$
Daily Precipitation (inches)	45.1%	$DailyP_{FB} = 0.0303 + 0.6260\ DailyP_{CMAP}$

Parameter	R-Square	Linear Model
Note: MinATFB: Minimum Air Temperature at Fort Benning		
MinATCMAP: Minimum Air Temperature at Columbus Metropolitan Airport		
MaxATFB: Maximum Air Temperature at Fort Benning		
MaxATCMAP: Maximum Air Temperature at Columbus Metropolitan Airport		
DailyPFB: Daily Precipitation at Fort Benning		
DailyPCMAP: Daily Precipitation at Columbus Metropolitan Airport		

As can be seen, the daily precipitation model does not have good predictor characteristics as it only explains 45.1 percent of the total variation observed at the Fort Benning installation. This is most probably due to the isolated showers that are very prominent between late spring and early fall. Albeit, the relationship is not strong, it is present and one might consider using the precipitation characteristics at the local airport as a predictor of the precipitation characteristics observed at Fort Benning if necessary.

Study two

Meteorological studies usually involve a detailed look at the typical parameters of precipitation, maximum and minimum temperatures, relative humidity, solar radiation and wind speed and direction, and the investigation can focus on a daily changes, a monthly trends, or trends over any long-term period of interest. Time intervals other than daily are usually expressed as averages or totals depending on the parameter under consideration. For example, temperatures on a monthly basis may reflect average maximum temperatures or the average minimum temperatures. Additionally, one could consider the average of the average daily temperatures and total precipitation for a period of interest. Although the use of these meteorological statistics is common practice, other indices, such as the Palmer Drought Index (PDI) or the Standardized Precipitation Index (SPI) could also be used to assist with the characterization of a region from a historical perspective. This second study made use of the SDI precipitation index in order to investigate the interdependent structure of the climate regions surrounding Fort Benning, Georgia.

The following paragraphs are a summary of the data from a historical perspective as well as a recent perspective. Correlation analysis is the primary basis of the summaries as well as descriptive statistics that describe the relationships between various meteorological parameters of interest.

Historically (1895 – 2006) rainfall amounts for the regions (Alabama and Georgia) surrounding Fort Benning ranged from a minimum of 2.29 inches during October to a maximum of 6.22 inches during the month of July. Historically, the average monthly precipitation was 4.33 inches with a standard deviation of 0.91 inches. At Fort Benning during 1999 - 2006, the precipitation totals ranged from a minimum of 1.95 inches for October to a maximum of 5.32 inches in March with an average precipitation of 3.34 inches and with a standard deviation of 0.88. Historically (1948 – 2006) the Columbus Metropolitan airport station reported a minimum average monthly precipitation of 2.21 in October and a maximum average of 5.64 in March. The average precipitation reported at Columbus AP was 4.06 inches with a standard deviation of 0.90 inches. The sampling window at Fort Benning truly represents a short period where precipitation amounts are much less than the historical averages observed at the NCDC Climate Region Divisions and at the Columbus Metropolitan airport. Drought indices researchers recognize the deficiencies of short term meteorological windows and hence, recommend at least a history database of at least twenty-five years in order to characterize the drought/non-drought conditions of an area.

Monthly precipitation amounts by location for the time period of August 1999 – December 2006 indicate the maximum monthly precipitation was 6.47 inches observed during the month of June in the Alabama region. The minimum monthly average of 1.95 inches was observed at Fort Benning during the month of October. Statistically, the largest amounts of precipitation occurred during the months of March, June and July and the least amount occurred during October. With regards to location, the average rainfall amounts in the three Alabama portion of the region recorded significantly more rainfall than the Georgia portion by an average of 0.4247 inches. The Columbus Metropolitan airport meteorological station recorded average was not significantly different from that recorded in the Georgia portion. Fort Benning, however, did show significantly smaller amounts of recorded precipitation averages than the Columbus Metropolitan airport where the annual average precipitation exceeded that observed at Fort Benning by 0.4278 inches.

Although the monthly average precipitation amounts varied significantly between locations, the relationships between these amounts were sufficiently high. The correlation between the monthly precipitation amounts observed at Fort Benning exhibited a significant relationship with all areas. The correlation between the amount of precipitation observed at Fort Benning and the Columbus Metropolitan airport was 0.9126. In the surrounding climate regions the correlations ranged from 0.7948 in Alabama and 0.8909 in Georgia. Correlations at these levels provide evidence that a relationship can be established and used at these various locations to help predict precipitation events at Fort Benning, GA on a monthly basis.

Annual precipitation serves as a part of watershed models and assists in the prediction of erosion. Annual precipitation was estimated from January 2000 through December 2006. Average annual precipitation observed at Fort Benning ranged from a minimum of 32.50 inches (825.50 MM) to a maximum of 47.58 inches (1208.53 MM) across the ten stations. Correspondingly, the regional data measured by the NOAA indicated that the Columbus Airport readings averaged 46.39 inches (1178.31MM) for the same sampling window. Likewise, the Alabama region reported a range of 53.16 inches (1350.26 MM) to 57.47 inches (1459.74 MM). The Georgia region reported annual averages ranging from 49.34 inches (1253.24 MM) to 50.66 inches (1286.76 MM). The annual readings observed at Fort Benning are consistently lower than those observed at the surrounding regions.

Among the ten MET stations on Fort Benning the average daily precipitation ranged from a minimum of 0.0912 inches/day to a maximum of 0.1186 inches/day observed at sites 9 and 3, respectively. The maximum precipitation amounts ranged from a low of 3.4409 inches/day observed at site 4 to a maximum of 5.4449 inches/day observed at site 5. The standard deviations were consistent and do not provide any indication of any site being more variable than any other site. The standard deviations ranged from a minimum of 0.2907 to a maximum of 0.4120.

According to the Western Regional Climate Center (http://www.wrcc.dri.edu/ spi/explanation.html), the standardized precipitation index (SPI), first proposed by Tom Mckee and others in 1993, is an index used to assign a single numeric value to precipitation totals so that comparison across regions with markedly different climate regimes can be performed. The SPI is an index value that represents the number of standard deviations that the observed value deviates from a long-term mean, for a normally distributed random variable. Since precipitation totals appear to follow a gamma distribution the equiprobability transformation is first applied so that the transformed precipitation values follow a normal distribution. The SPI can explicitly express the fact that it is possible to simultaneously experience wet and dry conditions at various time scales. Separate SPI values are calculated for a selection of time scales, covering 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 15, 18, 24, 30, 36, 48, 60, and 72 months, and ending on the last day of the latest month. For this study, only two time scales were considered – 1 and 3 months for the purpose of comparing monthly versus seasonal between 1999 and 2006.

The SPI values for the sampling year of 2006 were used to compare the index values for Fort Benning the Columbus Metropolitan airport and the regions surrounding Fort Benning in Alabama and Georgia. The time series of interest were 1 month and 3 months and only cover a historical span from 1999 to 2006. It is highly recommended that at least twenty-five years data be available, if not more, before SPI values should be computed; however, with only limited data such as what was observed at Fort Benning, these SPI values should only be considered for correlative measure only. SPI values are interpreted as follows:

+3.0 and above	exceptionally wet
+2.00 to +2.99	extremely wet
+1.25 to +1.99	very wet
+0.75 to +1.24	moderately wet
-0.74 to +0.74	near normal
-1.24 to –0.75	moderately dry
-1.99 to –1.25	very dry
-2.99 to – 2.00	extremely dry
-3.00 and below	exceptionally dry

The correlations were extremely good despite only seven years data for Fort Benning (for details see Appendix C, white paper C5, Dr. Dale Magoun). Historically, the 1-month time series SPI values for Columbus Airport ranged from a minimum of –1.04 to a maximum of +0.7 during 2006; whereas, for the 1999-2006 sampling years, the SPI values ranged from a minimum of –0.88 to a maximum of +1.07. For the 3-month SPI time series values, historically the 2006 ranged from a minimum of –1.19 to +0.67; whereas, the 3-month data ranging from 1999-2006 produced SPI values ranging from a minimum of –0.86 to a maximum of +0.79.

Study three

The purpose of this study was to use relationships developed from the MET data among the network of ten stations to determine redundancy, explore potential applications for the database, and to develop recommended actions for the network. For full details see the Appendix C, white Paper C2., by Dr. Donald W. Imm (Univ. of Georgia).

Using hierarchical, agglomerative clustering of the collective correlations associated between the 10 MET stations results in the following relationship between MET stations.

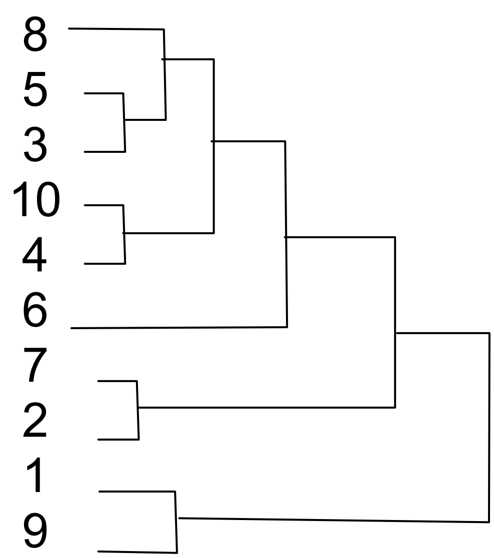

Figure 76. Collective correlations associated between the 10 MET stations.

The most strongly correlated stations are McKenna MOUT (4) and Lawson Army Air Field (10), the pre-ranger site (3) and Cactus Road (5), and those MET stations at Griswald (2) and Carmouche (7) Ranges. Again, these strongly correlated sites are not necessarily nearby stations. The weather stations at the Natural Resources Office (1) and the Alabama Site (9) are also strongly similar, relatively distant from one another, and both have precipitation patterns least like the other MET stations. This information can be used to identify redundant MET stations or to develop regressional relationships between stations that could then be used if a particular MET station was repositioned to a new location.

Application of weather station data

Once technological limitations are worked out, the MET stations will be linked with the existing GA network. Regional connections of MET stations can be used to improve atmospheric models such as those used to project smoke dispersion and plume behavior as well as local night time temperature inversion patterns.

These data are required for ongoing research involving watershed modeling (SI-1547, {Aquaterra}, BASINS model) as well as C- and N-cycling models (SI-1462 {Liu, USGS}, CENTURY-model based). Once developed and validated, this will be used for Fort Benning monitoring, these models allow for installation-scale estimates of carbon and nitrogen turnover, retention, and balance. The BASINS model will allow for evaluations of individual stream watersheds. Based on data and observation, some Fort Benning streams are more influenced by precipitation patterns and terrestrial water-use processes than others. Therefore, some streams would be more influenced by, or responsive to, land-use change than those which receive higher relative input from ground-water fed springs. In constrast, spring-fed streams should be evaluated using different parameters, such as off-post ground water dynamics or long term surface water-ground water flux. From a land management perspective, project-level hydrologic concerns and decisions should favor focus on those streams more strongly influenced by surface-water input patterns.

Several other models are highly reliant on accurate weather data, these include forest growth and health models as well as those that depict ecosystem dynamics (e.g., LINKAGES). With potential impacts of climate change, this information will also be valuable in projecting habitat change using ecosystem process models such as CENTURY, LINKAGES, etc. Tracking climate change may be particularly important at military installations because of the frequency and types of disturbance that may lead to earlier response of biotic communities to climate change through higher stress and lower resilience.

Independent of the BASINS modeling effort, MET station data is currently used to correlate hydrologic pattern, sediment movement, and stream turbidity. These factors are collectively used in monitoring stream conditions and biotic quality (e.g., RBP). Other research studies also continue to use MET station data (e.g ORNL DMPRC study).

Recommended Actions

Because of highly correlated temperature patterns and strong correlations of precipitation between some MET stations, the number of MET stations could be reduced to seven and still have comparable weather pattern coverage. Independent of access and logistics, the least valuable MET station sites are those at the Natural Resources office, pre-ranger site, and cactus microwave tower. In the short term, the needs for the BASINS model should also be considered. Continued efforts to link these weather stations should also be made because of local and regional concerns over smoke dispersion and air quality. If improved assessment of precipitation patterns are needed, an additional 15-20 automated rain gauges could be deployed within a particular watershed or across the installation. This may be necessary if local erosion risks are greatly elevated; this may be the case in some BRAC-related construction areas.

As MET station units are replaced, additional sensors should be considered. Sensors to monitor soil moisture and soil temperature would be useful for monitoring drought, fire planning, and developing estimates of soil moisture storage. These sensors should be placed in open areas and beneath a nearby forest canopy. Similarly, sensors for fuel moisture estimates should also be deployed to represent different fuel types. With KBDI, these estimates can be used for prescribed fire planning, and assessing the advancement and risk associated with wildfires. Again, sensors should be placed in open areas and beneath nearby forest canopies. Other additional sensors could include air quality and lightning strike sensors. Both could have value in tracking air quality and safety risk.

Water quality

Study four

The purpose of study four was to describe the relationship between total suspended solids (TSS) concentrations and turbidity. These parameters both indicate the amount of solids suspended in the water, whether mineral (e.g., soil particles) or organic (e.g., algae) and provide an estimation of erosion as a result of storm events. TSS tests measure and the actual weight of the material per volume of water, whereas, turbidity measures the amount of light scattered from a water sample (more suspended particles cause greater scattering). The difference in estimating techniques used to determine the concentrations of suspended material becomes important as calculations to determine actual concentration of particulate matter are possible with TSS values, but not with turbidity readings. Measuring turbidity, however, is less time consuming and can be done in-situ, whereas, TSS is a laboratory procedure. Thus, using turbidity to predict TSS in streams and rivers has been the topic of much research in recent years. (for details see White Paper C6, by Dr. Magoun)

In a study scientists collected data during and after storm events at four creeks – North Randall, Tiger Creek, North Upatoi and Pine Knot. The data was collected in late 2005 and spring of 2006. In the literature there appears to be two models that are consistently used to describe the relationship between turbidity and suspended solids. Laboratory experiments indicate that a linear relationship fits the data extremely well; however, one must be cautious of the fact that laboratory is very rarely replicated in field experiments and that scientific field data rarely obeys a linear relationship. However, both models were examined and interpreted for potential use (for details see Dr. Magoun's white paper).

The Fort Benning, data are best summarized by a log-linear model which best described the relationship between Total Suspended Solids (mg/L) and Turbidity. The least squares model is given below

$$\mathrm{Log(TSS)} = 0.8367 + 0.7778 * \mathrm{Log(Turbidity)}$$

and explains 70.4% of the total variation. It shows no indication of lack of fit and is supported in the literature by several researchers. Mathematically, this is an exponential model of the form

$$Y = \alpha X^{\beta}$$

For this set of data, the model is

$$TSS = 2.3087 * Turbidity^{0.7778}$$

This relationship adequately predicts concentrations of suspended materials from the more easily measured turbidity measures. Hence, one could then use this predictive model in their assessment of erosion as it relates to the total suspended solids observed in streams on the Fort Benning installation.

Land cover

Comparison of the Landsat ETM+ coverages for Fort Benning and within the HUC unit associated with Fort Benning and Columbus-area streams requires a brief explanation of differences and advancement in technique. Except when noted, the coverage boundary, and associated area, has not changed. Between the period of 2000 and 2007, a land exchange occurred between Fort Benning and the city of Columbus; therefore, the boundary of Fort Benning changed during this period for the most part these areas were dominated by planted and natural upland pine forest (Appendix C, White paper C3., by Dr. Donald W. Imm).

The initial coverage did not initially include an impounded portion of the Chatahoochee River that encompasses River Bend State Park; therefore, water estimates for on- and off-post open water area differs between Landsat coverages from 2000, 2003, and 2007. The River Bend SP area is referred to as “Not Mapped” Fort Benning Hectares. The relative amount of open water has remained fairly constant during the period of this study.

Off-post urban interface hectares were not initially classified in 2000; this area was likely dominated to by urban land cover with lesser percentages of forest, scrub/shrub, bare ground, paved roads, and herbaceous land cover types. Also, the land exchange led to some cantonment area being included within the non-Benning land cover classes.

To reduce classification error and increase interpretation, the 2003 land cover type classification began to class evergreen/hardwood forest areas separately. This forested component in the 2000 land cover type classification was likely to have included in natural evergreen, hardwood, and scrub/shrub categories.

To reduce classification error associated with recently burnt areas, the 2007 land cover type classification included a recently burn cover type. Considering the locations, the area included as recently burnt are likely to be natural pine, scrub/shrub, herbaceous, and lesser amounts of hardwood land cover types.

Table 30. Landcover types at Fort Benning, GA.

Landcover Type	Fort Benning (Ha)				Non-Benning (Ha)		
	2000	2003	2007		2000	2003	2007
Water	714	1031	1120		1235	1556	1870
Hardwood	26056	22023	19259		33193	26082	19350
Evergreen/Hardwood	-	17343	19241		-	12255	14355
Scrub/Shrub	9227	5759	6254		12671	12946	12308

Landcover Type	Fort Benning (Ha)				Non-Benning (Ha)		
Planted Evergreen	3801	1988	798		13094	12103	12036
Natural Evergreen	19721	14893	11930		5621	15795	17474
Burn Area	-	-	2733		-	-	802
Herbaceous	6206	3302	2019		19818	9538	8183
Bare Ground	1332	1392	4107		942	3534	7042
Paved Roads	1300	766	1053		2176	2117	2000
Cantonment	5426	5426	5206		0	0	32
Urban	-	0	0		-	11753	12240
Not Mapped	585	-	-		17522	-	-
Total	74368	73923	73720		106272	107678	107692

Overall, the pattern of land cover type change on Fort Benning is inconsistent with other data sources and land management directions (INRMP 2006, Prior et al 2007, Figure 77). The imagery data suggests that evergreen/hardwood area has increased since 2003, though this has been a primary focus for conversion to longleaf pine and mixed pine forest. Scrub/shrub has also increased during that period, while natural evergreen, planted evergreen and herbaceous land cover classes have declined. The decline in "natural evergreen" area may be due to conversion of off-site loblolly pine and mixed pine forest; however, when replanted one would expect an increase in herbaceous and planted evergreen coverage. Forest thinning of "natural pine" or "evergreen-hardwood" may result in spectral mis-interpretation as scrub/shrub immediately following the land management action. Some reduction in area of natural forest covers, through the establishment of the DMPRC, accounts for the increase in "bare ground."

Prior to full application, the following tasks should occur.

Recommendations

1) Improved "Ground truthing" using existing and additionally-collected canopy data may be needed to help redefine land cover types . These efforts should include defining the limits of compositional and structural ranges of each defined land cover type as well as improved definition of the habitat variability within.

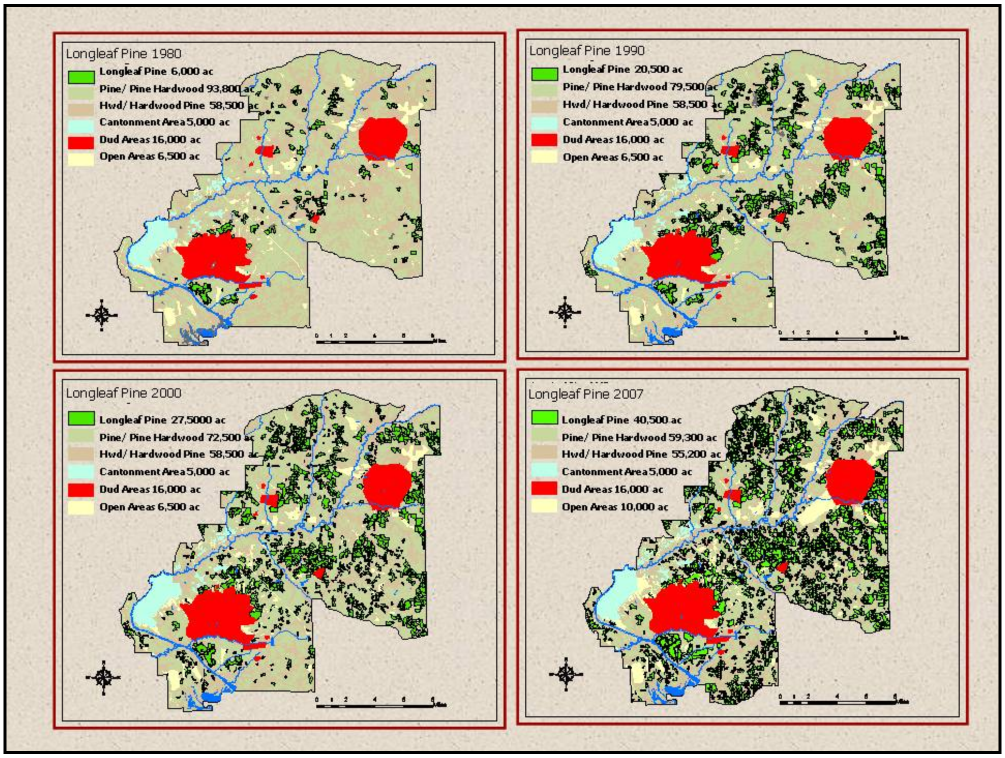

Figure 77. Landcover types at Fort Benning, GA.

2) Compare and analyze the algorithms used for classification. This includes comparison of different algorithms across different periods of coverage. Conceivably the spectral signatures, and resulting algorithms, associated with some land cover types (e.g., upland pine forest) will continue to evolve with improving resolution and land management advancement toward the desired open pine forest-grassy under story settings. Therefore, algorithms based on locales at or near the desired condition should be developed.

3) Though resolution accuracy has increased overall; consistency with other data may have declined. This pattern is particularly evident for natural pine, planted pine, and pine-hardwood coverages, which are high-priority land management settings. Potentially, resolution accuracy may have increased for non-Fort Benning areas, but declined for certain sections of Fort Benning. Therefore, some consideration should be given to analyzing spatial patterns of residual or classification error. Further consideration that open forest settings and finer resolution is resulting in a most forest stands being spectral mosaics that are more strongly influenced by under story and forest floor spectral signatures.

4) Comparison and integration with other remote resources such as LIDAR, hyper spectral imagery, and aerial photography is also needed. These other remote data sources will likely replace original data sources such as enhanced thermatic mapper (ETM+); therefore, a crosswalk between remote resource types is needed to retain interpretive value of the original imagery.

Application

Land cover classification is a critical resource for Fort Benning because it allows for remote assessment of conditions associated with difficult access. With the advancement of BRAC activities and further range usage, periodic access to remote areas to conduct field work will continue to be difficult; therefore, planning and environmental assessment will become more reliant on remote imagery and other GIS coverages. Further, multi-scale spatial assessments using field validated land cover classifications serves multiple purposes (watershed & water quality, forest growth & habitat quality, species suitability & connectivity, nutrient conservation & carbon budgets, etc.). Current and planned applications of land cover classifications include:

- Watershed models to estimate water-use, water-retention, and interception differences between forest types within a watershed. Essentially each land cover type is assigned water-use and transfer criteria that are field based and connected to topography and juxtaposition to streams. Spatially explicit watershed models can then be developed and correlated with hydrologic pattern of individual stream segments then cumulatively adjusted to various scales.
- Land cover classification is being used to assess C and nutrient dynamics. Each coverage type is assigned stocking values and functional process rates that are then partitioned across the landscape in proportion to occurrence. These values can then be cumulatively compared between watersheds or with the surrounding area.
- Assessments of habitat connectivity and fragmentation of RCW suitable habitat are made using forest and land coverage types. These same approaches can be used for other species of interest. Further work is needed in defining criteria associated with habitat assignment to land cover types as well as connectivity between existing and potential habitat units. Other remote data resources such as LIDAR and other hypers pectral coverages are more effective at delineating habitat and struc-

ture, these resources are not cost effective for assessing connectivity to off-post land conditions.

- Though hyper spectral coverages are more effective at detecting forest health problems, these data are more expensive and less likely to cover the entire area surrounding Fort Benning. Therefore, connectivity of spectral signatures between hyper spectal data and ETM+ data is needed to evaluate off-post conditions.
- Installation wide assessments of species richness patterns could be used to track the overall fitness of Fort Benning. Using species diversity equations recommended by the NRC report (2000); estimates of the impact of land conversion and land-use change could be made to estimate local & installation-wide change in species richness.

Stream ecology

The Rapid Bioassessment Protocol (RBP) was used to assess the wadeable streams on Fort Benning between 2002 and 2006 . Fort Benning occupies a transitional zone between the lower Piedmont and upper Coastal Plain ecoregions comprising evergreen, deciduous, and mixed forests. For this reason, there are fundamental differences in stream characteristics across the base. Because of the variability an effort was made to sample as many reaches on each stream as possible, however, many reaches were not accessible because of ongoing military activities or where streams crossed impact and DUD areas.

The RBP was used to characterize physical habitat quality at each reach. In addition environmental data describing pH, turbidity, conductivity, water temperature, and dissolved oxygen concentration also were collected to examine water quality conditions. Benthic macroinvertebrates were sampled at each reach to indicate biological variability among streams. Data analysis indicated that four specific variables were particularly useful indicators of stream condition at Fort Benning: pH, RBP, Hilsenhoff's Index of Biotic Integrity (HIBI), and %EPT or aquatic larvae of Ephemeroptera (mayfly), Trichoptera (caddis fly), and Plecoptera (stone fly). For each variable, we used median values from each sampling site to estimate conditions throughout the entire drainage. Based on this approach, our sampling sites represent approximately 58.3% of the base. Error in estimating conditions throughout an entire basin obviously can be correlated with basin size, sampling frequency, and other factors. Therefore we suggest conclusions based on these results be viewed as rough estimates of stream conditions at the installation. We also provide a brief summary of available

Total Maximum Daily Loads (TMDL) information for base streams. A summary of the findings follows, however for a full description of the methods, analysis and results see Appendix C, white paper C1, Mark Farr).

Water quality

The rate at which enzyme-mediated biochemical reactions occur can be influenced by the pH of an organism's environment. Therefore, the range and variability of pH as well as the buffering capacity of the environment can affect overall habitat suitability for aquatic macroinvertebrates in streams. Stream pH varies substantially among streams at Fort Benning depending on physiographic conditions. Although acidic conditions persist in most streams (pH < 7.0 in 79.8% of sampled basin area - SBA), streams in the upland portion of the base (e.g., Randall and Cox Creeks, Tar River) have pH greater than 7.0. Streams in the DMPRC portion of the base as well as Wolf Creek are very acidic (pH < 5.0) and represent ~26.9% SBA.

The ability for an electrical current to pass through water is said to represent "conductivity" of a stream. The amount of dissolved inorganic particles within the water column determines how well an electrical charge is transmitted. For this reason, stream conductivity is most affected by local geological properties and tends to be greater in streams associated with clay soils rather than bedrock substrata. Conductivity also is usually correlated with pH yet can vary with temperature and turbidity (conductivity can increase with both temperature and turbidity). Spatial trends in conductivity were, as expected, similar to those of pH. In general, streams with high pH (i.e., upland streams – Randall, Tar, Cox, Baker) also had the greatest conductivity measurements; these upland streams represented slightly greater than one-fifth of all sampled basin area.

Inorganic and organic particles suspended within the water column contribute to turbidity. Increases of turbidity are most often associated with runoff sediments carried overland into streams following rainfall events. Increased flow during precipitation events also causes resuspension of in-stream sediments. For this reason, any sources of erosion within a basin can lead to acute or chronic increases in turbidity and sedimentation. Small showers, animal crossings, etc...occurring upstream from sampling locations can result in misleading or variable estimates of turbidity. Almost half SBA exceeded 17.3 NTU (nephelometric units), although most of these streams were in the lower portion of the base (e.g., Oswitchee, Ochillee, Bonham). Randall, Pine Knot, Wolf, and Laundry Creeks had relatively low turbidity (<10.1; ~ 35.9% SBA).

Many biochemical processes in organisms as well as functional processes in ecosystems are regulated by temperature. In aquatic environments, water temperature affects rates of respiration, growth, production, and many other ecologically important factors. However water temperature can greatly vary diurnally, seasonally, with local weather patterns, atmospheric conditions, etc. Water temperature varied substantially among streams at Fort Benning (15-25^{o} C). Streams in the uplands section of the base (Tar, Randall, Long, Cox Creek) generally were warmer than those in the coastal plain portion of the base. Streams with lower temperatures usually were larger, deeper streams less affected by daytime heating of shallow margins or smaller headwater streams with increased shading by canopy cover.

Aquatic organisms require sufficient oxygen concentrations to allow underwater respiration through gills or absorption. Much like conductivity, turbidity, and temperature, dissolved oxygen concentration (DO) estimates at a stream site can vary substantially during a twenty-four hour period. Low DO often is linked to dramatic mortality events in aquatic habitat (i.e., fish kills) which may be associated with pollution or elevated nutrient levels. Over 93% SBA had median DO estimates greater than 7.0 mg/L. Of the other 5 streams, only Hollis Branch (DO ~ 4.85 mg/L) had a DO less than 6.0 mg/L.

Physical habitat quality

The RBP utilizes a visual habitat assessment system where 10 habitat parameters are scored from 0-20 (0=very degraded; 20=pristine). Scores are then summed to calculate an index value reflecting overall habitat quality at a site. The 10 parameters include habitat features both within and outside of the stream channel:

- **Epifaunal substrate/ available cover** – presence of substrate suitable for colonization by benthic macroinvertebrates and to provide cover for fishes
- **Pool substrate characterization** – diversity and stability of pool substrata
- **Pool variability** – abundance, size and depth diversity of pool habitats

- **Sediment deposition** – evidence of sedimentation present within the channel
- **Channel flow status** – proportion of channel submerged
- **Channel alteration** – evidence of dredging or channelization
- **Channel sinuosity** – degree to which the channel meanders
- **Bank stability** – erosion along each bank
- **Vegetative protection** – vegetative coverage along each bank
- **Riparian zone width** – depth and development of the riparian zone

RBP scores indicated moderate (RBP = 130-149; ~16% SBA) to good (RBP >150; ~67% SBA) habitat quality among most sampled streams. Scores from two upland streams (Randall Creek and Tar River – RBP < 130; ~18% SBA) indicated relatively low habitat quality. These two systems can be characterized as shallow with very little depth diversity, almost devoid of instream stable substratum, and comprising a loose, shifting sand substratum. All of these conditions are considered indicative of poor stream habitat, although these conditions are not uncommon among upland sandhills streams.

Biological indicators

Benthic macroinvertebrates are the most common group of organisms used for biological assessments in streams. We used Hilsenhoff's Index of Biotic Integrity (HIBI) and Percent Ephemeroptera, Plecoptera, Trichoptera (%EPT) to indicate differences in biological characteristics among streams.

Hilsenhoff's IBI estimates the cumulative environmental tolerance of macroinvertebrates sampled at each site. The resulting scores can range from 0-10 with low scores indicating a very low tolerance to environmental perturbation (good habitat quality). Median HIBI estimates indicated moderate stream quality among most streams; estimates ranged from 5.1-6.0 for streams representing ~74% SAB. One stream, Bonham Creek, had a median HIBI estimate below 5.0 (4.3; ~0.5% SAB). Although streams with HIBI > 6.0 represented ~26% SAB, the largest basin in this group (Oswitchee Creek) was only sampled once and comprises streams draining a DUD area. Furthermore, no HIBI scores exceeded 7.0 or indicated "poor" habitat quality.

Aquatic larvae of Ephemeroptera (mayfly), Trichoptera (caddis fly), and Plecoptera (stone fly) often are only associated with aquatic habitats of good quality. For this reason, the percentage of EPT organisms comprising the benthic macroinvertebrate assemblage can indicate overall habitat quality within a stream. Median %EPT varied greatly among streams at Fort Benning. Several streams contained fewer than 10% EPT organisms (i.e., Hollis Branch – 0%; Halaca Creek – 3%), and over half SBA had %EPT less than 17%. Samples from other streams contained over 30% EPT organisms (i.e., Randall and Little Pine Knot; ~23% SBA). However, more sampling will help determine whether these results reflect true variability in assemblage structure among streams.

Total maximum daily loads (TMDL)

The Clean Water Act of 1972 (CWA) set in place a means to monitor and regulate pollutants and discharges into the nation's waterways. Point source pollutants were the primary concern, however in since the 1980's, awareness has included non-point source pollutants. Sections 303(d) and 305(b) of the CWA set forth methods for states to monitor and report findings on the status of their waterways to the EPA. The primary method for reporting concentrations of pollutants is Total Maximum Daily Loads (TMDL). TMDL's are the sum of all allowable pollutants into a stream from point and non-point sources as well as a margin of safety. TMDL's must be generated for each pollutant found in a waterbody allowing for seasonal differences.

Streams on Fort Benning have been sampled for possible pollutants. Those streams not meeting water quality standards in the past are: Tiger Creek, Little Juniper Creek, Pine Knot Creek, Little Pine Knot Creek, Hichitee Creek, Little Hichitee Creek and the Chattahoochee River. The Chattahoochee River is the only stream listed as not meeting water quality standards for pollutants other than sediment (biota and habitat impacted).

The Chattahoochee River section from the mouth of Upatoi Creek to the railroad at Omaha, GA (~50 km) is "Not Supporting TMDL limits for Fecal Coliform (FC) bacteria." However, possible point sources of FC at Fort Benning are apparently not responsible for this rating. The National Pollutant Discharge Elimination System (NPDES) permits two sewage treatment plants at Fort Benning allowing for a geometric mean FC count of 200 per 100 mL. Monitoring of FC at the effluents has resulted in a geometric mean of 8.1 and 6.7 FC.

Urban runoff is thought to be the cause of the "Not Supporting" listing for FC. Runoff from farms, construction sites, and other wet-weather sources occur in three basic manners: stormwater, combined sewer overflow (CSO) and sanitary sewer overflow (SSO). Combined sewer overflow can cause risks to human and aquatic life, aquatic habitats and the recreational use of U.S. waterways. Fort Benning has initiated a Municipal Separate Storm Sewer System (MS4) plan to monitor and control surface runoff necessary under the Phase II NPDES Storm Water Runoff permit regulations.

The remaining listed streams at Fort Benning are impaired by sediments (biota and habitat impacted). Because they are Legacy sediments from previous land use practices no reduction is currently required.

Conclusions

Streams at Fort Benning are diverse in both habitat quality and condition. The confluence of multiple physiographic regions has resulted in both diverse chemical and physical habitat conditions among streams. Upland streams (e.g., Randall, Tar) are characterized as shallow, clear-flowing streams with very little pool development or instream stable substratum. Streams in the DMPRC portion of the base (e.g., Sally, Bonham, Little Pine Knot, Pine Knot) typically have very low pH but more depth diversity, variability in current velocity, and more stable substratum than the upland streams. Streams in the Ochillee drainage and most other areas in the southwestern portion of the base have moderately low pH with more diversity in depth and substratum; stable substratum and pool development is more prevalent in these streams.

Legacy effects from past landuse practices have influenced current conditions of Fort Benning streams. Although negative aspects of historical landuse may limit the upper limits of stream quality, the ECMI project has helped establish benchmarks upon which future changes in stream conditions can be compared. One of the longterm objectives of the program is to develop adaptive management tools to improve our understanding of how decisions can impact environments at the ecosystem level. The use of refined RBP methods along with the Georgia Department of Natural Resources IBI could result in the development of a system helpful for both: i) establishing current reference conditions (scores); and, ii) mitigating potential environmental quality impacts associated with resource management decisions at Fort Benning.

8 SERDP Ecosystem Management Project Research Initiative at Fort Benning: Monitoring Recommendations

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Executive summary

Five ecological studies were funded by SERDP (Strategic Ecological Research and Development Program) under the guidance of SEMP (SERDP Ecosystem Management Project). These studies identified a series of interlinking terrestrial and aquatic ecological conditions that are directly impacted by training as well as past land-use and current land management. These findings are further defined in the summary and synthesis section of this final report.

Monitoring recommendations are to focus on five principal areas; a) landscape condition, b) watershed condition, c) longleaf pine matrix DFC attainment and forest health, d) hydrology and water quality, and e) TERS species occurrence and habitat. These focus areas are most appropriate because they can be integrated across scales, they are focused toward compliance and environmental management initiatives, and they can be shown to be directly associated with Benning training and management activities.

Landscape condition is best assessed through the use of dynamic process models that are implemented through the use of existing or attainable GIS coverages and imagery. These coverages are then "ground truthed" through information gathered from field work associated with other research and monitoring inititives as well as forecasting the effects of planned land management activities. Critical features that were identified include aspects of ecosystem quality, sustainability and health, arrangement, and measures of patterning (e.g., size, shape, transitional contact, and adherence to landscape contour, etc.). Various coverages have been used (ETM+, hyper-spectral, IR photography, LIDAR, etc.) and none was found to meet all needs, but patterns of each are specific to certain questions. The question of coverage frequency, type, seasonality, and application will continue to be addressed regionally and nationally with the advancement of technology. The development of landscape models for target species, conditions, and progress toward DFC expectations remains a research need. The recommendation is to continue to track installation scale change in ecosystem type, quality, condition, arrangement and efficacy to site conditions and how they impact (isolation barriers, corridor changes, etc.) on RCW recovery, TERS status, water quality, DFC attainment, and sustainable use. Other recommendations are to follow the influence of

landscape change on other biological features (neotropical migratory bird communities and nesting patterns).

The relationship between watershed land-use especially condition, quality, and proportion was found to strongly influence hydrology, stream quality, and aquatic habitat associations. The most critical land-use factors were identified to be the proportion of bareground, road-stream crossing frequency, and road density. Other site specific factors include:
(1) streambed and streambank geometry relative to flow patterns,
(2) health, efficiency, and effectiveness of the transition & riparian forest,
(3) carbon and nutrient sink functioning across the transition forest,
(4) assessment of site condition index and collective change in site quality relative to sustainable land-use expectations, and (5) local connectivity and assembly of habitat and forest types relative to DFC landscape objectives. Important parameters should include soil quality assessments based on texture and organic material, understory composition based on functional group and lifeform, and canopy health, composition, and structure. Recommendations are to use nested sampling designs that can be extrapolated to higher landscape scales as well as define local variation of habitat conditions that can then be associated with species-specific habitat requirements. Focus areas should be both those with expected increased change in land-use (e.g., proposed BRAC ranges) as well as reference watersheds that typify the landscape.

Our recommendations are to focus future initiatives on land management strategy-defined DFC goals and targets; then develop a clear and consise means of qualitatively measuring progress toward expected land conditions. This includes flexible consideration of alpha- and beta-level diversity that may be imbedded within the definition of "successful" management. A series of studies were conducted that directly reflected the implications of tracked vehicle activity; these findings, as well as realistic expectations that consider differences in past land-use, need to be used to develop landscape level projections for future forest health assessments as well as ancillary conservation and land management planning. Further work appears to be needed relative to cumulative training and land management impacts on the existing forest and how these impacts may differ from findings from studies conducted elsewhere on landscapes that have different land-use histories or landscape settings within the Coastal Plain. Our recommendations are to continue to track forest health and development in areas being used for RCW recovery as well as other upland pine settings (e.g., young longleaf forests). Further, better use of other sampling initiatives (e.g., forest inventory) or existing plots and information (e.g., LCTA) is needed to detect the advancement of potential forest health programs. Forest health detection strategies should conform to standardized techniques (FHM/FIA protocol) and forest development focused on DFC target conditions. This information, with TERS site data and watershed data, will be integrated with GIS coverages to better define landscape patterns of forest health and development.

Hydrology, water quality, and stream condition were found to be strongly influenced by terrestrial land-use, physiographic region of drainage, and land history. Water chemistry was less responsive to differences than suspended sediment loading and stream bed stability. The greatest differences were found to be associated with storm-water flow, though detectable differences of base flow were also apparent. Our recommendations are to continue to track suspended materials and water flow for all major streams on Fort Benning. These data should be consolidated using a hierarchical model that reflects aggregating inputs from multiple drainages. In project areas, biological quality and habitat conditions should continue to be assessed using the Rapid Biological Assessment techniques. The most sensitive biological features that should be monitored include benthic invertebrates and as appropriate dominant fish species. If severe change is detected then equipment to detect change in other physical and chemical parameters should be deployed.

Limited SEMP research focused on TERS species status, location, and condition. However, other studies have focused on the development of habitat group-defined TERS site characterization and dynamic response models. Further, some work was done to experimentally characterize the impact of tracked vehicle training and land management activities. Further work is needed regionally on defining and characterizing these species and their environment. Our recommendations are to implement existing habitat forecast models as well as continue to support data integration and research associated with these species and their response to land management and training.

Overall recommendations are to strengthen the tie between compliance-based requirements, DFC goals and objectives, and continued support of a sustainable training environment. Monitoring information is needed to: (1) assess conditions for purposes of a sustained military environment,

(2) to redefine and adjust landscape expectations, plans, and priorities, (3) to meet regulatory compliance needs, (4) for quality assurance and assessment, and (5) to identify new research needs and provide information to address new inititiaves. Because greater priorities are placed on some issues and areas, the most appropriate way to efficiently and effectively meet these objectives is to use an approach comparable to medicine, whereby diagnostic decision trees are used to identify problems associated with areas or topics of concern.

Further, analysis and interpretation of monitoring information should aggressively use apriori information as well as monitoring data that reflect known expectations and thresholds. This approach allows for interpretation and forecasting in the form of problem likelihoods and frequencies that can then be prioritized. The advantage to a maximum likelihood or Bayesian belief network approach is as follows: (1) model development proceeds from goals to input, (2) attention is focused on what isn't likely to result in desired "outcomes," (3) the need for input accuracy is governed by outcome expectations, (4) in contrast to structured-equation-models, cumulative error that develops from step-wise protocols does not exist, (5) suited to manager insignt and apriori information (e.g., unquantified past land-use), (6) replicates are unnecessary to form functional response estimates, and (7) the approach is outcome based not process based, therefore, well suited for empirical modeling. This approach focuses monitoring toward capturing information concerning the most critical components that you have conficence in, and directs research toward the most critical compenents that you have least confidence in. Finally, affect of those parameters that have direct "ecological importance," but are difficult to monitor can be minimized through multiple decision steps and model structure that emphasize the indirect effects on parameters that are easier to measure.

Finally, landscape analysis using GIS and imagery resources as well as installation-wide weather and streamflow data will remain necessary to address potential relationships between climate change, continued military training and the potential increase thereof, and the interaction between both. These analyses will play a future role in assessing the condition and state of Fort Benning resources and how its role may change at the regional scales. Assessment of patterns associated with increased fragmentation and cross-boundary change will have a role in identifying potential barriers to planned activities (burning, RCW recovery, water-use, infrastructure development) both on and off post.

Introduction and background to monitoring

Recent reviews have identified effective monitoring programs as having the following characteristics: (1) monitoring is designed around clear and compelling scientific questions, (2) implementation plans include periodic review, feedback, and design adaptation of accepted methodologies, (3) monitoring is based are carefully selected metrics designed to address future needs, (4) data quality and consistency in sampling is maintained, (5) protocol for data availability and archiving is in place, (6) the monitoring data is continually examined, interpreted, and presented, and (7) monitoring as part of an integrated research program. These recommended characteristics for an effective monitoring program are not unique and have been identified by a variety of other papers. The purpose of monitoring is to track progress, impact, and status of noteworthy environmental characteristics as they pertain to land-use, management actions, and inherent change. Because management actions tend to be focused on a “worst first” approach, monitoring should also be focused on lower-bound thresholds that identify degrading conditions. Monitoring upper-bound thresholds remains important because it reflects attainment relative to planning and regulatory commitment.

Selection of parameters for sampling to meet monitoring objectives is also a critical component of monitoring. Dale and Beyeler (2001) identified several scientific criteria for technically effective ecological indicators. A good indicator should: (1) be easily measured, (2) be sensitive to stresses on the system, (3) have a predictable response to stresses, (4) be anticipatory of impending change, (5) predict changes that can be averted by management actions, (6) have a known interaction and response to baseline conditions, (7) have low variability in response, (8) integrate important features across gradients and within the system, (9) be reflective of appropriate temporal and spatial scales, and (10) be relevant to the management and land-use objectives. In addition to these characteristics, other criteria that reflect budgets, staffing, as well as goals and priorities are also important.

Monitoring initiatives are often based on attempting to meet either regulatory requirements or cursory assessments of features that are associated with generalized objectives. Greater emphasis is needed to evaluate the effectiveness of land management activities and tracking landscape level features associated with the sustainability of the existing state and condition. Unlike research which tends to be focused on projected concerns, monitoring is designed to evaluate changes associated with past actions or agglomerative impacts. Because many monitoring programs are initially research based, at least from a technique standpoint, relevant extrapolation and expansion to meet monitoring objectives can be difficult. Through the Delphi process involving Fort Benning land managers, Dale (2006) identified the following elements as being critical to a monitoring program: (1) help resource managers comply with environmental regulations (e.g., Endangered Species Act), (2) provide feedback on the effectiveness of management practices, (3) identify quantifiable management targets, (4) information gained should be comprehensive and integrated, and (5) maximize the ratio of sampling effort to information gained; whereby sampling design should be cost effective and reflective of information need.

Equally important is how the monitoring information is used and implemented into management decisions. As part of the integration report, Dale (2006) identified (Figure 78) relationship between monitoring, land management, and land-use. In this particular case, the desired future conditions (DFC) are assumed to be the “environmental goals.” Monitoring information should be suited to meet regulatory requirements, provide insight into the progress of land management initiatives toward environmental goals, and provide necessary baseline information that can be used to assess change as it is associated with land-use conditions. Secondarily, monitoring information can be used to redefine and refocus management techniques and objectives toward realistic short-term and long-term goals as well as provide baseline information to other user groups or to parameterize ecological models.

As a secondary focus, monitoring should be used for forecasting and detection of future potential risks. Even with non-specific support these baseline initiatives should be maintained because the impact of regional changes in population growth, industry and agriculture as well as potential climate settings should be monitored and then integrated with other regional partners. Certain expected changes have already been identified and can be incorporated into long-range monitoring strategies. Knowledge of changes in baseline conditions can be used to make adjustments in land-use at Fort Benning and within the surrounding area. Specifically, forecast monitoring can be used to assess realistic expectations for the suitability of a landscape to provide a sustainable training environment as well as suitability of existing environmental priorities.

Transition and flexibility within integrated monitoring plans

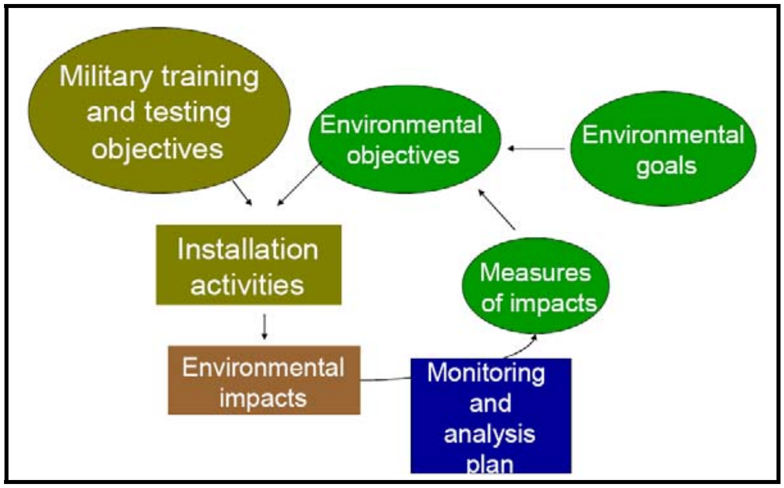

Figure 78. The monitoring and analysis plan.

A SEMP transition plan was developed and the report (Fehmi, Balbach, and Goran, 2005) identified several possible means developed by a selected council that included SERDP and SEMP research investigators as well as land managers. The technology transition plan was proposed to include three phases; transition of research finding to Fort Benning for monitoring plan development, transition to other federal installations along the fall-line region, and lastly, a transition to other organizations through incorporation into national networks. Since the identification of these three phases, some advancement has been made for some of the objectives; perhaps more importantly, unexpected pit-falls in transition have been identified and are being resolved.

Transition from research to monitoring involves adjustments in practicality, intent, and scale. Research is generally focused on precisely defining the distribution of points about a mean and then comparing that distribution to one associated with a different or modified condition. In the case of monitoring, little effort is placed on evaluating the distribution about the mean or improving precision because few, if any, replicates are taken; but rather, accurate and predictable estimates of the mean are need as to represent the condition at a particular location and time. Just as research strives toward a universal understanding of a relationship, monitoring strives to improve a local cause-and-effect understanding of a particularly relevant relationship. Therefore, to move from research to a reasonably achievable monitoring program several things must occur: (1) sufficient causal or correlative information must be available to allow for reasonably accurate predictions using fewer data, whereby data acquisition has been reduced in scale, magnitude, intensity, frequency, or type, (2) using methodologies that have high accuracy at appropriate time and space scales, and (3) if not directly linked, then through an accepted crosswalk, the monitored feature must represent the necessary condition. One of the most valuable elements of past research is that it can be used to “populate” or estimate expected conditions within a monitored setting. Though different methodologies often yield different estimates, the general condition is represented by all estimates for a particular parameter. Through structured ecological models (SEMs) these estimate values can then serve as a starting point for further evaluation, particularly if the original information is used “populate” baseline data sets using probability-based techniques. Many suited SEMs are available for application; application would simply require an evaluation of model performance to determine its sensitivity and where it best reflects ecological conditions. These assessments can be achieved through use of comparable data sets from other locales or through boot strapping of source data. Dale et al. (2006) further elaborate about other research-monitoring relationships as well as the needs of monitoring and land management to effectively represent the ecosystem. The important point is that some thought must be given to how and why research technologies are being adapted into monitoring programs.

Flexibility in monitoring is always in question; the monitoring techniques deployed today were meant to answer the questions from yesterday and may not be of value in assessing the questions of tomorrow. Again, through the development of generalized SEMs that are probability-based and populated from available data sources, a suite of questions or criteria to evaluate and monitor can be identified and linked to existing knowledge. Flexibility is further enhanced if a stepwise approach to monitoring is taken. Using this method, each monitoring result that exceeds a threshold or condition leads to the deployment of an additional technique that is based and complimented by the results of the previous technique. A stepwise approach means that a planned succession of monitoring techniques have been identified to further refine the estimate of magnitude, scale, or causality of a detected monitoring problem. At each successive step the manager has the opportunity to determine whether sufficient information has been gathered to develop a management action for the identified or developing condition. In general, the initial monitoring steps are likely to be broad in scope, inexpensive to deploy, but correlative with other ecosystem processes. The latter techniques are likely to have higher expense, less likely to be extrapolated across scales, locations, or conditions, but more likely to represent causal ecosystem factors. Finally, this approach could not possibly identify all of the successive combinations of necessary monitoring techniques, however, the most expected problems and causes can be identified.

Lastly, monitoring is often focused on either temporally or spatially static estimates whereby a state or condition is assessed and then reassessed to determine change between t_0 and t_1 or between location x and y; however, the spread of "change"' and shifts in the rate of change (decelerating, accelerating) are generally not evaluated. Assessing changing rates of change (e.g., the second derivative of a slope along the length of a curve) is necessary for risk evaluation and prioritization, which is one of the principal tenets of monitoring.

Monitoring cost and expectations

Costs associated with monitoring can be attributed to the following; a) upfront equipment or contract costs, b) sample collection costs, c) sample processing, and analysis costs, and d) sample interpretation and integration costs. Most laboratory and imagery costs are upfront expenditures that involve equipment purchase, advanced training, and elevated labor costs. Generally, indicators that require laboratory analysis are more exacting, less extractable to nearby locations or time periods, and have higher per unit costs. Unfortunately, these indicators are often at or close to the functional condition that may be responsible for regulating the disturbance response. Other less expensive "field" monitoring techniques tend to be less exact, more "cumulative" of time and spatial condition, more extractable to other locations and time periods, but less apt to be directly reflective of the regulating or functional condition.

When it comes to monitoring, managers are often hopeful of having affordable, and minimal monitoring that may rely on *a priori* knowledge for the deployment of particular locally exacting monitoring technique, but, the *a priori* knowledge comes from having the analytical capability of inference from a nested set of "coarse-grained" field monitoring techniques. Such a scenario would obviously be the most realistic and cost-effective for reasonably potential problems, but without background information becomes heavily based on regional inference, policy, and gestaldt.

A typical "worst case scenario" is continued monitoring efforts, and expense that would be more effective elsewhere, that result in continuous collection of poorly correlated data that often includes parameters of limited in value. The "bulk data gathering" approach often does not reflect the necessary suite of potential problems nor provide the tools of detection. This approach also generally results in infrequent analysis and posterior inference ("Aaah, we should have noticed that pattern sooner"). Another common feature in monitoring programs is the inclusion of components that are seemingly for the "greater good." This is acceptable when monitoring devices are inclusive of parameters (e.g., water temperature in remote water sampling devices); however, when particular measures are made independent of "canned" devices, managers should question how that information is being used.

Finally, evaluating monitoring costs prior to implementation is important. With the exception of project level monitoring, monitoring costs need to be seen as a commitment to acquiring necessary information without an expected date of practical application (e.g., biological assessment). Further, monitoring data becomes valuable over time and space, but once certain aspects of knowledge are gained, the periodicity and numbers of samples can be adjusted. For example, once stream bed sediment movement is seasonally characterized for base flow conditions, continued sampling frequencies can be adjusted toward evaluating storm flow patterns and sufficient base flow information to maintain optimal correlative understanding. This approach has been successfully implemented at many LTER sites, where continued and improved understanding of past or necessary research objectives is maintained through reduced sampling efforts focused toward specific locations that, through correlation, are representative of other locales and conditions. In fact, the underlying hope of the SEMP projects was to develop a short list of indicators and thresholds that could be used to represent changes in other parameters and conditions, and then used as "canaries in the mine" to initiate further sampling if problems appear to be developing.

Monitoring intent and program drivers

The purpose for monitoring can range from (1) needs to periodically document changes in states and conditions at representative locations, (2) establishing reactive sampling to define the scope, extent, and scale of a particular problem or potential problem, or (3) monitoring to determine functional cause-effect relationships of a particular problem so as to devise corrective action. Monitoring is an initiative intended to capture change in ecosystem, community, and population process and condition. Change in process or condition can be attributed to change in "outside" influences (e.g., global climate change, neighborhood land-use patterns, etc.), change associated in ecosystem (e.g., successional processes) or biological inertia (e.g., species invasion), change associated with direct and indirect land-use action (e.g., military training, development, forestry practices, etc.), or non-directional change associated with random (e.g., drought) or sustaining events (e.g., fire in fire-adapted habitats).

Other considerations in the development of monitoring programs include constraints associated with statistical interpretation, practicality, and relatedness to a controlled or regulated activity. Further, monitoring is often conducted to validate change in condition or assessment of program advancement (e.g., project level quality assurance/quality control). Sample design and statistical interpretation are limited by the scale and frequency needed to detect change at a particular level. Importantly, integrating the scale of maximum interpretation with the scale of practical need is important in defining sustainable monitoring practices with consideration of alternative natural resource investments (e.g., land management investments, restoration, research, outreach, etc.).

When developing field monitoring designs several issues must be addressed and include:

1. Scale of needed interpretation (identified)
2. Scale for minimum variance (size and # plots)
3. Scale for maximum interpretability (maximized statistical relationship with independent variables and minimized variance)
4. Scale for minimum sample size (# plots).

Each of these issues directly relate to different metrics of "effort" (e.g., budget) and expectations from a monitoring intiative. Unlike research, in most cases statistical validity can not be maximized at scales appropriate for management nor are the responses so well understood that they could be used to directly equate to differential management actions. With management priorities in mind, Emphasis should be placed on what meaningful conditions are most likely to change and where. Inferences and existing knowledge bases should be used to develop expected and alternative responses as well as identify areas of unknown responses. These "areas of unknown response" should be used to develop the next set of research questions within the context of what is known. The "expected and alternative responses" should be used to develop future adaptive management strategies to influence response and used to develop step-wise diagnoses for continued change.

Recommended monitoring elements

Landscape and installation monitoring

A wide variety of applications can be developed from analysis of imagery and photographs. With advancing technology and improving resolution, imagery signatures for patch types, and the variance within, can be better defined. This is important for evaluating constancy of condition and variance patterns can be used to evaluate patch heterogeneity, which may reflect patch quality. Accurate characterization of spectral traits associated with "good" quality habitats is necessary for strengthening spatially-explicit models as well as assessing changes in forest health or habitat condition.

Potentially, these parameters along with patch size patterns could be used to define desired distributions of patch size, patch heterogeneity, and variance between patch types. Presumably, endangered species recovery will gradually move away from minimum size thresholds toward recommendation standards based on patch size distributions and connectivity. Relative to connectivity, the advancement of technology and resolution should result in multi-scalar definitions of fragmentation and assessment of diffuse boundaries. Different species groups have respond to different scales of fragmentation and boundary delineation; thus, assessment of these traits should reflect differential needs of target species. For example, what may be fragmented habitat to large mammals (black bear, white-tailed deer) may simply be differential habitat units for small species. The converse pattern could also be true; whereby, what would be habitat heterogeneity to large mammals could be isolating barriers to smaller species. At least, 3-4 scales of habitat quantification, fragmentation, and connectivity should be used, each reflecting a target condition.

Another application of imagery and GIS resources is to evaluate the changing conditions of the surrounding landscape and how that influences the regional role of Fort Benning. Changes in regional expectations and restrictions can redefine priorities, objectives, and operations.

Installation scale analyses using imagery information provide context and connection of site specific monitoring and research to broader scales or similar scales in other areas. This is important for developing accurate characterization of landscape features that are used by other regional air- and water quality models (e.g., Basins watershed model). Local habitat models are also reliant on accurate interpretation of imagery and the timely detection of change.

Invasive species detection using imagery resources has been an ongoing regional and national initiative. Remote detection of early problems is paramount to realistic, cost-effective control of these species. Currently, many of the major invasive species concerns lie northward in the clayey piedmont areas (e.g., Kudzu, though locally present on Fort Benning) or southward near the coast (e.g., cogon grass); however, expanding populations of Chinese-privet (*Ligustrum sinense*), japanese silk grass (*Microstegium vimineum*), Japanese honeysuckle (*Lonicera japonica*), and Chinese wisteria (*Wisteria sinensis*) do exist on Fort Benning. High density, restricted populations of giant reed (*Arundo donax*) tallow-tree (*Sapium sebiferum*), japanese climbing fern (*Lygodium japonicum*), and golden bamboo (*Phyllostachys aurea*) are also present near riverine habitats. Other unregulated invasive species that occur through out the area include Bermuda grass (*Cynodon dactylon*), bahia grass (*Paspalum notatum*), weeping lovegrass (*Eragrostis curvula*), shrubby lespedeza (*Lespedeza bicolor*), Japanese clover (*Kummerowia striata*), silk tree (*Albizia julibrissin*), as well as various planted escaped species. In each case, these species displace other native species and influence system dynamics that control nutrient availability, fire behavior, and native species establishment.

Application and further refinement of existing "tools" and resources can be achieved through characterization of existing patches on the landscape. This work is necessary to further implement existing classifications (e.g., TNC alliances and associations). The TNC classification system is accepted in concept but has not been applied to land management decision making. Application could be further aided by within group characterization and then comparisons with existing forest & landscape conditions. Such a tool could be used to prioritize management planning as well as assess progress toward desired goals.

Geographic information system data sources

Depending on activity patterns, use satellite imagery and aerial photography at 3-5 year intervals to characterize and account for vegetation and disturbance types. This periodicity would accommodate land management affects and be sufficient to capture military training patterns. These tasks should consider change associated with on and off-post watersheds as well as adjacent areas that are subject to change due to Fort Benning activities (e.g., BRAC). The expected tasks would be as follows:

- Using LIDAR and selected hyper-spectral band widths, develop and use precursor techniques for identifying areas of declining forest health. Research continues to investigate the most appropriate techniques for identifying these problem areas. Challenges include influences of understory and ground cover on the spectral signature associated with partially open pine and mixed forest canopies.
- Characterize understory type (e.g., NDVI, normalized discriminant vegetation index), density, and cover; then associate the frequencies of these types and conditions with forest type classes, general land-use, legacy land-use, and soil-topographic settings.
- Calculate percent cover of general vegetation cover types and associate with soil classification and topographic characteristics. The objective is to define the highest probability condition for a particular landscape-vegetation setting. As part of this effort, define the typical "within state" variance of condition in terms of TNC classification groups at the alliance and formation levels. These patterns can then be used to estimate general cover classes and expected ranges of different life-form classes (Dale 2005, Collins 2005).
- Define patch characteristics such as patch numbers, patch size distribution, patch dispersion patterns, patch perimeter to area ratio, etc. These criteria define home range suitability, habitat partitioning, and potential dispersion or migration pathways for a wide variety of species. Percent cover of cover types, Total edge (with border) of patches, Number of patches, Mean patch area, Patch area range, Coefficient of variation of patch area, Perimeter to area ratio of patches, Euclidean nearest neighbor distance of patches, Clumped distribution of patches.
- Develop vegetation classification that is suited for input into other landscape or process-level ecological models.
- Develop classification to accommodate differences in N- and C-budgets for different vegetation types as well as AET, precipitation, interception of precipitation, and water storage of the terrestrial component of a

generalized watershed model. A dynamic model of N-, C-, and water cycling should be developed to address future initiatives. Currently, most information is available to parameterize such models.

- Use imagery to periodically update and improve digital elevation models
- Use changes in DEM to estimate erosion between time periods and identify changes in exposed soil in heavily used areas and along roadsides near streams.
- This information is currently used for range planning and construction. Installation-wide assessments of erosion "risk" could be used for project planning.
- As needed, use Near Infrared Reflectance Spectroscopy (NIRS) and partial-correlation coefficients to estimate Total C, Total N, and Total P terrestrial concentrations for some areas. To successfully use these techniques, better defined expected thresholds and conditions are needed. With continuing legislative focus on carbon cycling, expectations may soon be defined for public lands.
- Use LIDAR, hyper-spectral band widths, or ground penetrating radar to estimate depth to water/parent material in "high erosion risk" areas.

This will improve estimates of soil water retention capacity and turnover rate; hence, better correlations with stream flow estimates

Installation weather, air quality, and water quality sampling

Continued monitoring at current scales is necessary to evaluate potential changes in weather patterns that may affect expected land-use outcomes and sustainability. This includes evaluations of past operations and associated conditions (burning, herbiciding, forest health, logging). Further, with integration of other Georgia weather stations, this information could be used to detect and forecast climate change patterns.

Establish four primary weather stations and seven secondary weather stations associated with either large watersheds or principal training areas. The primary weather stations will be linked to "Georgia Net" weather stations, while the seven secondary weather stations will function to document variance between primary stations.

Because of the dependence of air quality on weather and air movement patterns. Air quality parameters should be measured at established weather stations. Air quality parameters should be consistent with those needed to evaluate air quality concerns as well as those satisfactorily capable of representing particulate input associated with military training (e.g., dust) and prescribed burning.

Establish Sampling Stations to measure or assess the following parameters for stream base and storm flow associated with input and export from Fort Benning.

Continue to sample suspended sediment concentrations and correlate with turbidity.

At permanent locations that are randomly stratified, periodically assess bed sediment type & rate of sediment movement (deposition, loss); this data, cover data, stream classification data, and estimated water flow can be used to characterize stream habitat types.

Establish staff gauges and water level monitoring equipment as to utilize developed rating curves and then evaluate patterns of water flow velocity and volume.

As needed, use remote sampling equipment (stationed, deployable) to continuously, periodically, or seasonally monitor factors that influence stream and water quality. These may include factors such as water temperature, water pH, DOC, BOD, turbidity, etc. These factors will be defined based on correlative or causal relationships with stream and water quality conditions of concern.

Establish stream sampling stations to characterize the habitat conditions (size, flow, stream bottom, amount and type of organic debris, etc.) associated with biological information from rapid biological assessment.

Using models as a predictive tool

Adequate sampling that is appropriate for multiple scales is difficult to maintain across a dynamic landscape. Three stages are needed in establishing a model and encorporating data: (1) construction, (2) development, (3) calibration and (4) validation. Model construction should follow a logical sequence of steps that replicate those in nature, correct "flow" of existing or developing models is the most critical component of a successful ecological model. Temporal and spatial scales should be representative of input data sources and the model outcomes. During development an existing or newly created model should consider correlative and statistical relationships between the data within the boundaries of logical construct of ecological understanding. Attributes with highest statistical strength and greatest logical impact should be emphasized within the organized body of the model. The model should be calibrated and populated with existing data and process rates from on-site or nearby locales. The sensitivity of rates and fluxes as well as the range of data should be assessed during calibration. Finally, once the model is developed it should be validated using independent data or at least a sub-set or the original data through boot-strapping or cross-validation.

Because of the expected use by Fort Benning, ecological models should be process-driven, but outcome-based. A variety of statistical and dynamic flow models were developed by SEMP and SEMP-related projects, future emphasis should consider other techniques to improve applicability. One technique is structured ecological models (SEM), though imbedded with dynamic processes, SEM's allow for outcome emphasis being placed on attributes of interest. SEM's provide both correlative and equitable representation of the installation and associated activities, but allow for scientific interpretability that can signify change and lead to further inspection via additional monitoring or research. Structured Bayesian models have greater allowances for forecasting impacts as likelihoods or probabilities of particular outcomes, and Bayesian approaches accommodate data gaps through inferenced knowledge and correlative relationships across multiple scales. In both cases, model structure greatly influences forecasted outcomes.

Lastly, with expected increases in training loads at Fort Benning, accessibility to areas necessary for monitoring is expected to decline. Thus, remote sensing and model forecasting will become more emphasized and necessary to accurately project environmental conditions at Fort Benning. Further, these tools will become more valuable in prioritizing access and coordination of land management activities. Below is a listing and short overview of SEMP-related models that were developed or models that are currently being considered for application.

Imagery vegetation analysis

Imagery-based vegetation classification (e.g., NDVI, NLCA), with periodic ground validation, can be "populated" with habitat characteristics from existing data and permanent plot monitoring, and then used to predict habitat type, amount, and quality using accepted habitat models (BIRDHAB, HERPHAB, etc.), or other models and equations specific to a particular species (e.g., gopher tortoise) or habitat condition (e.g sandhill barrens).

Imagery-based vegetation analysis, with developing and known spectral signatures, can be used to identify areas of future potential health risk. These techniques can be further refined by tracking areas of known composition and health (monitoring plots, past research sites, FIA sites, etc.).

Periodic coverage would allow for estimates of changes in elevation, LIDAR can also be used to estimate depth to impeded penetration which is generally parent rock, fine textured horizons, or water tables. Through subtraction and estimate of "surface" horizon thickness can be made and then tracked with elevational change, to estimate sediment accretion and loss. A similar procedure is likely to be possible for stream elevations and estimates of bed sediment depth.

TSS and stream bed loading models.

This is an ongoing SERDP/CERL funded project whereby TSS within water during storm events and base flow is estimated using a turbidity probe that has been correlated with volumetric estimates of sediment concentration. Once the streams are gaged to represent flow volume by water level measurements, then estimates of total volumes of suspended sediment can be made for individual watersheds. Further, estimates of oncoming and outgoing sediment concentrations can also be made for particular streams or stream segments.

Land condition threshold criteria

Risk assessment is needed to determine if the watershed relationships identified by Dale et al. (2006) can be used to develop risk-based criteria for a model that evaluates placement of future projects or prioritizes watershed erosion control efforts. Currently, a series of projects are attempting to characterize state-transition models that will be suitable for this use. One problem relevant to military training impacts is that a complete state change generally does not occur; more often, a decline in quality and capacity for sustainment occurs or devestation is nested or imbedded within broader landscapes.

Landscape-urban interface models

RSIM (Dale, 2006) and mLeam (Westervelt, 2005) are landscape based models that are reliant on patterning general classifications and inferred spatial dynamics across boundaries. The emphasis areas of both models are the interplay between human-induced land use patterns with TE species habitat suitability as well as air and water quality. Prior to implementation, both models would need further validation and analysis. To date, joint model performance has need been completed and would be needed to determine if a single source of information results in conflicting answers. Necessary parameters for model performance are already available; this model is dependent upon categorical shape files (e.g., forest type) that are assigned probability-based criteria. Both models are reliant on spatially extrapolating information from functional response equations to predict process dynamics across the landscape.

Soil quality threshold model

This model was developed by Garten and can be used to assess expectations of monitored locations relative to soil and vegetation recovery. This model could also be used to prioritize soil recovery efforts. The soil quality threshold model was used as a basis to develop a comparable GIS landscape model capable of predict landscape areas with potential excess nitrogen (PEN); which if concentrated within a particular watershed would increase the likelihood of excess nitrate and nitrogen movement into stream water. This model is a component of the RSim model. The soil quality assessment model requires input information concerning (1) initial amounts of aboveground biomass (i.e., forest volume estimates), (2) initial soil carbon stocks (i.e., soil quality), (3) relative recovery rates of biomass (i.e., forest growth rate), and (4) soil sand content (general estimates are acceptable). The companion GIS Model, that is capable of predicting non-point C and N sources by habitat on the landscape, has a model structure that includes; (1) a tree biomass submodel that predicted aboveground and belowground tree biomass, (2) a litter production submodel that predicted the dynamics of herbaceous aboveground and belowground biomass, (3) a soil carbon and nitrogen submodel that predicted soil carbon and nitrogen stocks (to a 30 cm soil depth) and net soil nitrogen mineralization, (4) an excess nitrogen submodel that calculated the difference between predicted plant nitrogen demands and soil nitrogen supplies, and (5) excess nitrogen movement submodel to predict the fate and rate of transfer toward wetland systems.

Some concerns over the model outcome have been expressed, particularly those associated with the N-cycle. The model does not consider relevant inputs (N-fixation by free living bacteria, N-fixation by legumes) or relevant losses (denitrification, volatilization of ammonia, etc.). The model also does not consider site-to-site differences in resource availability nor within-stand dynamics.

Watershed model

Several other watershed models exist, all with different strengths and weaknesses and application. EPA recently developed a landscape hydrology model, BASINS, that is being calibrated and "field tested" at Fort Benning through funding from SERDP. This model will predict the impact of watershed conditions on water quality and associated attributes that effect stream biota and ecological function. This SERDP funded project (PI:Aquaterra) was initiated in May 2007. This model will allow for an evaluation of watershed change and its impact on biota, chemistry, sediment movement, and waterflow.

An interagency group also developed a compartmental WEPP (watershed erosion potential prediction) model to predict the impact of management actions on watershed condition. The latter uses standard forest classification data and compared to the EPA model has two or three input parameters that are more relevant to Fort Benning. However, the EPA model may be more compatible with Storm water Drainage Models, which are also needed at Fort Benning. The WEPP model can incorporate instability caused by burning, but has been criticized because it is a compartmentalized static-flow model; therefore, most applicable to larger unit scales. WEPP model inputs require six information inputs that include: soil textural characteristics to predict water holding capacity, topographic characteristics, land condition characteristics (forest types, ages, etc.), road infrastructure patterns, location and climate, and ground cover characteristics.

Multivariate comparisons of vegetation conditions and qualitative DFC concepts

This approach can be used to assess expected progress, as a function of management activities, toward a DFC concept. The basic intent is in multi-dimensional space define a distribution of points that represent the DFC condition, then through vector analysis using repeated samples over time or spatial distributed data, again in multi-dimensional space, define the progress toward the condition. The "tricky" aspect is defining the distribution of points and describing the pattern. Assumption of "normality" is not necessarily correct but various analytical tools can approximate the data behavior within "normal" space.

The utility will be repeated use of this technique will allow land managers to assess progress toward expected DFC conditions and will allow for prioritization of land management activities to achieve continued change on the landscape. For example, a decision could be made to emphasize habitat improvement in a particular area, or to improve a particular set of conditions (advancing improvement of the best settings, emphasizing change in the worst settings, etc.). Emphasizing qualitative characterization is important because it allows for fair assessment of habitat differences by different groups that have different expertise and it allows for equal comparisons of conditions over a number of years and in different locals. Further, with changes in DFC definition, comparisons can be adjusted. Lastly, using qualitative strategies in assessment provides a documented and repeatable means of comparison that can be shared with other interested groups.

NIRS remote sensing techniques to predict soil nutrient concentrations

Near Infrared Reflectance Spectroscopy (NIRS) for soil analysis is rapid, low-cost technique for determination of several individual soil biogeochemical properties and direct evaluation of derived soil quality metrics or indices. The technique can be deployed using hand held or vehicle mounted scanning devices as well as devices attached to air craft. The technique assessed 20 soil biogeochemical variables, and was used to develop a robust partial least squares (PLS) model for independently predicting TC, TN, and TP. The results indicate that near-infrared spectroscopy coupled with partial least squares can be a useful and inexpensive alternative to expensive and time consuming lab analyses. These parameters are particularly useful in assessing watershed dynamics of chemical transfer from terrestrial settings to streams as well as useful in improving forest growth, health, and productivity models.

Water quality regression equations

Parameters were originally identified through correlative relationships and then through step-wise regressional analysis used to develop equations that depict watershed & training attributes to water quality features which can, and have been, correlated with SBI and other rapid bio-assessment indexes (e.g., EPT). These equations would need to be assessed for a broader range of conditions (e.g., 100 year storms, major droughts, etc.) and then be evaluated using other streams at Fort Benning and within the local region.

Site condition index

Parameters are generally transferable or sufficiently correlated that it could be used to characterize past and present data sets by watershed or installation. Currently, the source equations are not readily available, though the identified parameters can be extrapolated from other data sources to GIS coverages. Necessary parameters include; A-horizon thickness, soil compaction, % soil organic matter, % litter cover, % canopy cover, basal area, tree density. These parameters will be sampled as part of permanent monitoring plot strategy. Therefore estimates will be made for individual plots to determine trends for particular locations. Plot scores will be compared to other techniques, such as that used by Collins (SEMP final report), to evaluate prediction quality. At the landscape scale, sufficient information exists to “populate” various groupings (soil series, vegetation types) with auto-correlated probability distributions. Once “populated” with information, installation-wide or location-based (e.g., watershed, training compartment) GIS maps will be possible. An iterative process will be used to a) adjust and improve Site Quality Index equations, and b) adjust and improve partial correlation coefficients used to “populate” GIS groupings.

Habitat models

BIRDHAB (Hamel, 1992) and HERPHAB (Wilson 1994) are qualitative and categorical habitat models that are capable of predicting qualitative habitat suitability for a variety of species. These models do no consider population dynamics nor factors that influence principles of migration or partitioned habitat use. The habitat input requirements are general and include those parameters associated with forest classification (stand age, dominants, basal area, site index, estimate tree size, etc.); however, improved versions incorporate finer-scale information (e.g., CWD amount on forest floor, canopy openness, etc.) that is acquired independently or as part of forest inventory analysis (FIA). These models doe not incorporate stochastic processes or species population dynamics.

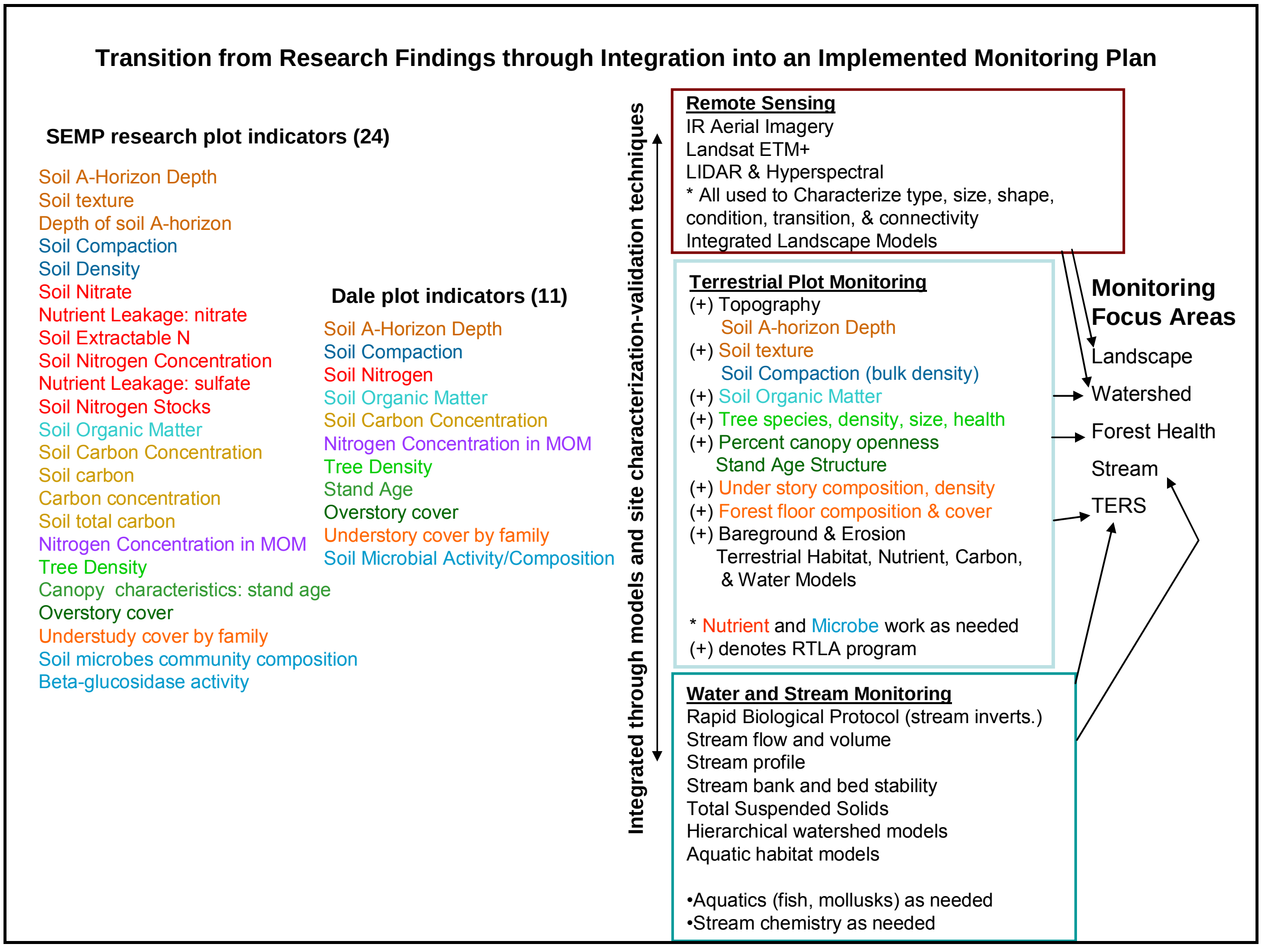

Figure 79. Transition from Research Findings through integration into an Implemented Monitoring Plan.

A variety of other models are being developed to address specific habitat types or species groups. Examples include a SERDP funded initiative (SI-1302, PI: Sharitz, SREL) that will yield a “Gopher Tortoise Habitat Model,” “Sandhill Habitat Assessment Model,” and “Sandhill TERS species model.” Elsewhere in the region other initiatives are in place to develop similar predictive tools. Similarly, models could be developed for species associated with the longleaf pine matrix using the data currently collected to meet the needs for the RCW foraging matrix. These species may include listed SAR and state-sensitive species including plants, gopher tortoise, Bachman’s sparrow, and so on.

Ecosystem monitoring

Strategy for nested-plot terrestrial sampling

Depending upon the variable, several different sampling schemes are available to represent different types of data with different distributions and variance patterns. Generally, monitoring efforts involve sampling multiple variables that are then correlated to develop a conservative, stable status assessment. The involvement of multiple samples generally results in a sampling scheme that adequately samples for one or a couple variables and over samples for several others. The result is a great deal of data redundancy for several variables. Further, when tied to "generalized" sampling strategies that are designed to adequately cover a variety of ecosystems and conditions, then further redundancy and over sampling is added. However, when using a generalized scheme, most of the sampling uncertainty has been resolved. One suggested approach is to use sample designs comparable to those used by USFS for forest inventory analysis (FIA) and forest health monitoring (FHM), both of which occur at Fort Benning. These designs have a series of "stratified levels" of sampling intensity in which additional sampling locations or intensities can be accommodated but are not necessary to monitor for all "questions." These techniques are also appropriate in scale for land use patterns at Fort Benning and provide data that is similar to that proposed by Neufeld (Fort Benning Conservation staff) for RCW habitat assessments as well as by Addington (Fort Benning TNC) for assessment of upland pine management. Often overlooked in analysis, more generalized techniques can accommodate a wider variety of data sources and are less influenced by sample design and source. Such a technique would include posterior-based maximum likelihood estimators whereby a priori information is used to modulate expected trends within the data. These techniques, and other Bayesian formats, are also less dependent upon repeated sample representation or accurate categorical characterization (i.e., unknown past land management affects can then be accommodated).

Recommended application strategy

Consistent with Dale's findings (SEMP Integration Report, 2006), recommendations are to establish an integrated set of monitoring points that are focused toward assessing the status, condition, and progress toward the primary desired future condition (upland pine matrix). Though different in objective, these plots will be comparable in scale and share common parameters with periodically sampled FIA/FHM plots, LCTA plots, RCW habitat monitoring plots, and watershed assessment plots (described below) as well as previous inventory and research data. To best use background data, points will favor past research locations.

To adequately represent upland pine conditions, 100 stratified, random plot clusters will be position in accessible locations with near equal representation of upland pine types (longleaf pine, mixed yellow pine, and pine-hardwood), age classes (25-50 yr, > 50 yr), and surface soil settings (sand, loamy sand, and fine textured soil classes). Because of the necessity to assess current forest health issues; as available, past research or monitoring sites will be used to provide baseline information concerning past forest conditions and recent land management activities will be used to characterize potential sources of forest health change. At each site a variet of tasks will be conducted to characterize conditions, these include:

- GPS locations taken to link with location with other installation information and data coverages (e.g soil classification, DEM).
- Canopies will be sampled using four 1/5 acre circular plots that are equally positioned within 1 Ha. Sample by document dbh, spp, and estimated health class for each individual. Include standing snags. Samples will include stems >20 cm. Use collected information to classify into timber types and condition classes. This approach is consistent with existing Forest Health Monitoirng protocols.
- The sub-canopy and woody understory will be sampled using center nested 100 M^2 plots. Plots will sample stems 1-20 cm, gt 1 M in height.
- Shrub and woody vine cover classes will be sampled using two near-corner positioned 2x2 m plots (shrubs are those less than 1 cm dbh or 1 m in height).
- Ground cover will be estimated using four near-corner 1x1 m plots, whereby sixteen-0.25 m^2 plots) nested in a 4 m^2 location will be used. Species cover class will be used to estimate species dominance patterns, unknowns will be classed by family and life form.
- Estimate overall cover by % vegetation, % needle/leaf litter, % woody fuels, % bare ground.
- Using a densitometer, estimate canopy cover at each 100 m^2 corner point.
- Sample soils for compaction (penetrometer) at surface, 10, 20, 40 cm depths. Roughly 10-15 samples per location with eight stratified locations within each of the 100 m^2 plots.
- At five randomly selected locations within each 100 m^2 plot, measure the depth of surface horizon, and evaluate general textural classes for 0-10, 10-20, 20-40 depths. When appropriate, depths to impermeable horizons or mottled clay will be recorded.

- The collected soils will be pooled in the field, using the collected soil samples identified above, bag/label, weigh, dry, reweigh, and then retain for combustive estimates of MOM within the surface soil (0-10 cm).
- Characterize ecological setting using a series of qualitative questions: (1) recent burn y/n, (2) topographic setting (slope, aspect, juxtaposition, etc.), (3) document litter type and amount (fuel classes used for fuel models would be sufficient).

Recommended "as needed" monitoring

As needed, a series of breeding bird census points will be established to assess change in neotropical migratory birds. Many Neotropical migratory bird species have been identified as having critical declines over the past decade (Partners In Flight, Audubon); so in support of the migratory bird treaty act, we propose monitoring in areas that are expected to experience conditional shifts in habitat. Songbirds are an important monitoring feature that integrates conditions at scales beyond those used for vegetation surveys and is sensitive to changes in connectivity. Changes in breeding bird populations are reflective of short term change in habitat quality. Bird populations are useful indicators because they integrate various elements of habitats and are well studied, thus, accurate forecasting of habitat suitability is possible.

As appropriate, other faunal species may be monitored to detect finer scale or broader scale changes. These species include broader scale cohorts such as whitetail deer, bobwhite quail, coyote, feral hog, and herptofaunal communities as well as finer-scale indicators such as ant and butterfly communities.

Forest Health concerns should address attempt to address causal relationships as well as underlying factors that influence forest health and pathogen outbreaks. When forest health concerns are documented a qualified forest pathologist should be deployed to assess the problem at particular locations as well as in the surrounding area. Soil scientists and ecologists are also necessary to assess factors such as recent weather influences, soil compaction, nutrient conditions, training, and other elements associated with indirect influences on tree vigor, root condition, pathogen life cycles, and vectors of transfer.

Loss of productivity and vigor at a particular setting is often due to either nutrient relations or recent weather patterns. Other important growth factors such as light and moisture typically define composition and productivity. Typically, nutrient problems either involve the availability of macro nutrients or unbalanced nutrient settings. Because organic matter plays such a critical role in nutrient storage, release, and regulation of soil ecology, assessment of different forms of C may be necessary in some settings.

Slow or failed recovery of heavily disturbed areas may also require assessment of seed movement, connectivity to similar habitat settings that can provide sufficient seed and pollinators, and recharacterization of the capacity to be productive (soil quality).

Small stream watershed sampling

Terrestrial watershed characterization

Establish an integrated set of 60 watershed assessment plots within three selected watersheds (20 in each).

Like the previous set of permanent plots described to assess upland pine conditions. Nested plots with similar design characteristics and common parameters will be established within three previously sampled watersheds. These plots should be comparable to periodically sampled FIA/FHM plots, LCTA plots, RCW matrix plots, and upland pine monitoring point (see above) as well as previous inventory and research data. Sample plot placement will be truncated toward transitional habitats. Parameters will include those used in other plot level sampling efforts as well as quarterly sampled nested lysimeters at the wetland transition. Watershed selection will be those selected for water quality monitoring.

Based on SEMP studies the following terrestrial landscape characteristics, along with disturbance intensity, were found to be correlated with stream hydrology, water quality, or biological conditions. These parameters can be periodically assessed by watershed via imagery or recent, accurate GIS coverage layers.

Riparian buffer width. This parameter has been suggested to be correlated with stream quality in some areas, and insignificant in other studies. A common management objective is to meet or exceed state recommended

BMP's, though the specific width and corresponding effect is not consistent.

Riparian sediment deposition rate. A SEMP study found small amounts to sediment deposition to negatively impact vegetation health and condition and which may reduce overall riparian forest health and effectiveness.

Percent total area of unimproved roads and trails. Collectively, the sum of this parameter and % bare ground on slopes >3% had a strong negative association with various water quality and stream quality measures.

Road density and number of road crossings. These parameters may need further characterization as far as "trails," "unimproved" roads, etc. as well as "hardened" crossings vs. incidental or historic crossings. Collectively, both were negatively correlated with streambed sediment movement and some water chemistry concentrations. Of the tracked conditions, these and well as road area are manageable parameters that's can be reduced through proper infrastructure planning.

Percent upland bare ground on slopes >3%. This parameter represents bare ground area resulting from military training; therefore, the relationship with stream and water quality indicates that at some training level resulting in greater than 10-15% open ground results in a exceeded threshold and rapidly declining water quality condition and rapidly increased risk of bulk erosion toward stream drainages.

Catchment-scale watershed and landscape monitoring objectives

Plot information will be used as a means of continuing classification distillation and refinement of "land management meaningful" vegetation types and associated hyper-spectral signatures. These classifications will be used to proportionately represent the landscape relative to water and nutrient budgets; therefore, distillation and refinement of the classification will improve model estimation accuracy. Terrestrial water and nutrient modeled budgets will be parameterized using original SEMP work and then associated with stream loading. Further, these classifications will improve the efficiency of land management planning by enabling the capacity of efficiently identifying areas of natural connectivity between habitat units.

To assess chemical transfer from the terrestrial to wetland systems, lysimeters will be seasonally used at some plot locations. Knowledge of these transfer rates is critical to understanding water quality issues because wetlands function as “sinks” therefore, input and output dynamics are indicative of wetland health.

Characterization of sediment exposure and movement. Knowledge of exposed soil surface is critical in assessing surface erosion risk. Sediment flux assesses the rate of movement toward the wetland and stream.

Exposed soil surface reflects the amount of area subject to uninterrupted surface water flow as well as directly impact energies from precipitation.

The net sediment flux of specific locations can be used to estimate the volume of sediment moved.

Methodology to evaluate “rill” or gully erosion potential or change in extent has yet to be developed.

Landscape affects of on- and off-post land-use patterns will be assessed using vegetation characterization and Breeding Bird Census (BBC) methods. These assessments will be conducted in the three identified watersheds as well as north boundary watersheds including off post watersheds that are expected to experience “high growth and development.” The focus of these efforts will be to:

- Assess the impact of land-use change on “interior forest breeding bird species.” These species are those that have significantly declined nationally over the past 10 years and are defined as those that require corridors and connectivity as well as habitat units greater than 40 acres.
- Assess the occurrence pattern of brown-headed cowbirds. These birds are parasitic on other nesting birds and highly representative of forest fragmentation patterns.

The presence and relative percentage of urban bird species such as starlings, English sparrows, robins, will also be used as an indicator of development impacts.

In adjacent training lands, BBC will be used to assess the impact on savanna and old field species. Density of these species types reflects habitat quality and condition, particularly the amount of perennial cover. The relative presence of shrub species (Indigo bunting, ovenbird, etc.), reflects successional degradation of early successional types.

In conjunctions with objective 4; characterize the status and condition of these vegetation types relative to:

- Habitat integrity and sustainability for target species:
- Identified SAR and state sensitive species,
- SEMP identified plant indicator groups,
- PIF-identified at-risk neo-tropical migratory birds.

Changes in the presence and abundance of targeted invasive species. Monitoring invasive species is of significance due to the documented effect on ecosystem processes as well as Executive order 1332, which states that federal government facilities will regulate and control invasive species.

Provide periodic monitoring updates relative to the state and condition of known state-sensitive plant and animal species. Monitoring will be conducted periodically to assess the collective impact of land-use (e.g., invasives, training, forestry practices, etc.) in the immediate area as well as the change in the local habitat setting.

Location, topography and physical soil features (soil texture, soil depth, compaction, etc.) of all monitoring sites will be initially sampled. These features will be resampled as necessary (e.g., significant training impacts as noted by observed monitoring features). These features, as well as the other monitoring features, will be used to characterize the observed monitoring data patterns.

Recommended stream sampling strategy

Establish sampling stations at three locations within three selected watersheds (see terrestrial monitoring) to measure or assess water flow, water quality, and habitat quality. Sampled parameters will be those expected to be associated with sediment movement (suspended, non-supended) during base and storm flow.

Stream site habitat conditions as well as benthic diversity will be quantified on a 3 year cycle at 3 locations of the three catchments to characterize stream habitat conditions. Sampling will be conducted during late autumn periods.

At three locations, of each of the three catchments, three “Grab” samples for biological and chemical analysis will be collected quarterly (prior to storm flow, during storm flow, and following storm flow); whereby, quarters are defined by “water year” information. During the sample collection period, portable equipment to quantify stream and water conditions will be used to sample various metrics that are associated with biological activity rates. Sampling will be conducted during late autumn periods.

At the project level, water and stream quality should be measured above and below the disturbance source and then again at two locations further down stream. Comparison of the above and below source sampling points will allow for an assessment of the magnitude of impact. At the two locations further below, an assessment can be made to evaluate spread and mitigation rate of the disturbance characteristics through natural attenuation.

An approach to adaptive monitoring

Monitoring resources should be applied to areas that are either at-risk of further change or have exhibited unexpected loss character or stability. Essentially, like all management decisions, monitoring implimentation can be based on a) reliance on past or “recommended” methodologies, b) effectiveness of modified techniques, c) adjusted based on data, d) adjusted based on relationship to priorities, e) based on “gestaldt” or insight, or combinations therein. Overall, a means of testing concepts and validating expected results from management actions is necessary to land management operations it allows for a proactive stance and response to regulatory expectations. The alternative is reactive application of untracted “mandated” change. Under these conditions, field observations and monitoring have little value and progress and advancement toward improved application, reduced cost, and accelerated progress toward management goals is minimized.

What is needed is most needed is the development of logical progession and connection of past information that is based on data observations, expected change in a particular area, or insight based expectation. These “cross walks” between current monitoring and past initiatives are critical for interpreting perceived issues and land management threats. Further, integration and extrapolation of information is needed to represent unsampled areas or measured. The integration and extrapolation should be based on known or understood relationships, be expressed as likelihood frequencies.

Diagnostic decision trees

Generally the relationship between observed ecological problems, diagnostic indicators and regulatory processes, and causal forces can be represented by an hourglass shaped relationship. Causal forces are usually limited to the most common rate limiting factors (e.g., available light, nutrients, water) that lead to differential responses. Decision trees can be constructed much like classification keys used to characterize species, diagnose health problems, or partition causality. These relationships can be represented by decision trees that initially diverge, then potentially converse toward common methodologies to regulating factors. With each successive step within the decision tree, technical expertise and or monitoring cost to represent an equivalent area are generally increased. Hence, continued priority assessment should be made relative to resolving the source of a perceived problem.

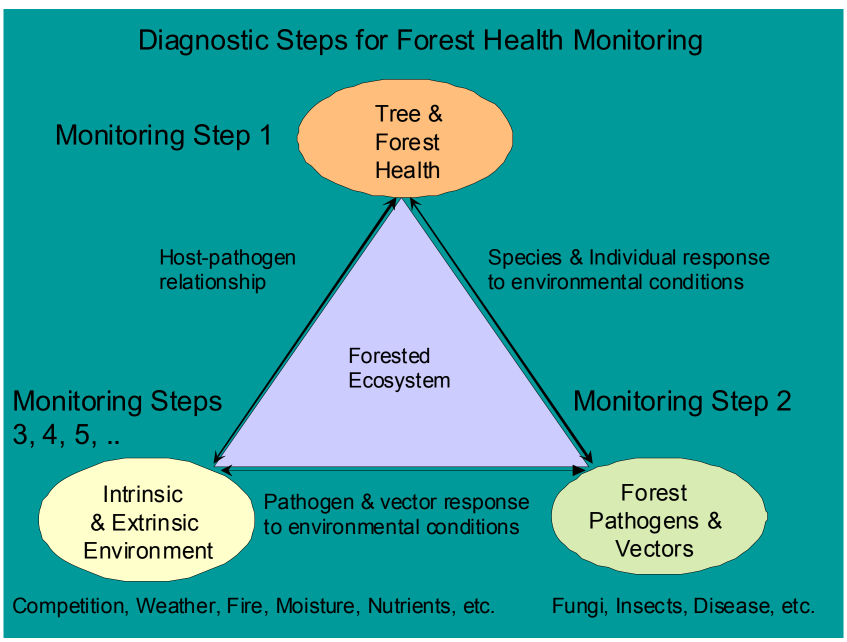

Figure 80. Diagnostic steps for forest health monitoring.

A general rule of thumb is that indicators with greater real time interpretation (acute response) have greater direct dependence on other parameters that must be sampled as well as greater temporal and spatial variation. Thus, require more samples for appropriate evaluations to be made. Those indicators that tend to be aggregating and cumulative are associated with chronic response, or of a functionally expanded scale, often require assessment at expanded scales, with consideration of lag times, and are more difficult to associate a "cause-and-effect" relationship with a particular problem. Full understanding of an indicator is important because indirect relationships often dominate the responsiveness and response to unassociated problems can often result in "false-positive" interpretations. Finally most regulatory criteria are "condition" oriented as opposed to process oriented, thus, logic and decision to solve a condition may be different than that used to evaluate a condition. Finally, because the decision trees tend to converge on similar indicators, the interpretation of these indicators will be improved with continued collection of data; thereby resulting in improved definition of the indicators and well as documentation as to the effectiveness of these indicators in predicting problems.

Diagnostic Decision Trees are useful if monitoring is being done to characterize the scope, extent, and scale of a problem as well as identifying the functional features that have led to current condition and state. Again, it's important to note that characterization of problems is often sufficient in monitoring. Not all observed problems can be corrected, fiscal limitation and the lack of cost-effective technology; however, these issues can be identified and prioritized for future initiatives.

An example of a Diagnostic decision tree for forest health is provided below and based on figure 80. These relationships and logical sequences for monitoring can be developed for a variety of problems and assist in identifying what additional research information is needed. The diagram above essentially, the first monitoring step is to periodically track tree and forest health using standardized, repeatable methods such as those used for Forest Inventory Assessment (FIA) and Forest Health Monitoring (FHM) (USDA-FS, 2001). The second step is to determine what pathogen is causing the problem, and the remaining steps are designed to identify what environmental conditions and land-use actions are allowing the pathogen to become problematic.

Diagnostic decision tree example: A stepwise approach to declining forest health or vigor

1a. Observed forest health decline is localized and can be attributed to an obvious condition. This would include observations of unhealthy trees in areas subjected to physical damage (harvest, training), flooding, chemical imbalance, fire, etc. No additional Monitoring is needed.

1b. Based on the observed pattern of local decline, immediate management action is necessary. In many circumstances, forest health problems are detected too late; therefore, management actions to remove unhealthy trees is necessary, however, the remaining trees and adjacent trees should be evaluated to determine the source of the problem. Continue to evaluate tree and forest health conditions as well as pathogen occurrence frequency: step 2.

1c. Observed decline in forest health and growth without suspected causality. This can be done a) qualitatively via stand exams or site visits, b) via analysis of permanent plots (ex. LCTA, FIA or Forest Health Monitoring (FHM) standards as well as periodic sampling of established monitoring plots to identify to source of decline, and c) Using LIDAR or a hyperspectral signature capable of detecting precursor information to forest health problems. Evaluate potential causal reasons: step 2.

2a. The Identified pathogen(s) is/are native species that is negatively affecting tree health at frequencies higher than predicted or acceptable levels. Different levels of acceptable decline or mortality need to be defined through management objectives. The identified pathogens may have individual or cumulative impacts. To determine why the pathogen has become problematic an assessment of environmental conditions is needed. Again, cumulative effects need to be assessed, for example the combined effects of drought-soil quality-fire intensity on tree vigor and health. Evaluate potential environmental causes: step 3.

2b. Identified pathogen is a non-native species that has become established. When a new pathogen is detected, several questions need to be addressed. What are the effects? What species or conditions seem most susceptible? How wide spread is it? What is the rate of spread? What mitigation steps can be taken to reduce spread rate or symptoms? Therefore, accelerated monitoring and research actions are needed. Once the problem is understood, then operation and monitoring action plans and protocols can be developed and implimented.

3a. Weather patterns indicate anomonalies that may have influenced forest health. Direct weather pattern influences that affect tree health and vigor are usually apparent. These would include drought as well as damaging effects such as ice storms and wind events. In these cases, the capacity of trees to ward off pathogens and insects is reduced. In most cases, the effects of these factors are diminished within 2 growing seasons. Indirect weather pattern effects are less apparent, these would include factors that affect the life cycle of the pathogen or facilitating vectors. An example would include warm winters which allow for greater pathogen reproductive success.

3b. No obvious differences in recent weather patterns over the past 3 years. Evaluate other potential environmental causes: step 4.

4a. No recent fire activity.

4b. Recent burning in areas without historical burning. Often, upland areas that have not been burnt have rhizospheres that extend into the surface litter. Fuel build-up and root advancement into these areas can result in high root mortality and delayed tree mortality.

4c. Recent burning, no indicators of catastrophic effects are apparent but heavy military land-use or recent land management activities are evident. Evaluate other potential environmental causes: step 5.

4d. Recent burning, with indicators of local damage (scorch, heavy fuel consumption, etc.). Cumulative impacts of environmental factors and repeated frequent burning can result in increased elevated tree mortality, particularly in areas poorly suited for sustained fire management. Evaluate other potential environmental causes: step 5.

Once general conditions are assessed, characterization of the physical environment is needed to detect a degraded condition. Characteristics include soil texture and other edaphic and topographic features that contribute to site index estimates. This includes an initial assessment of stand density to eliminate the possibility of causal responses to density-dependent factors such as competition or tree-to-tree transfer.

Assessment of soil characteristics that may be associated with a weakened condition. These include surface horizon thickness, compaction or loosening of surface soil, and impact on factors that may affect rhizosphere activity. Each of these factors have direct impacts on tree root health and vigor, hence whole system health, as well as indirect or chronic influences on resource availability and competition patterns.

Once soil characteristics are assessed, local water availability can be evaluated relative to season, demand, and storage capacity. Periods of drought (as can be documented by weather station data) along with assessment of competing biomass and composition can be used to determine the magnitude of water stress and documented using pre-dawn water potentials. Again, pathogen vectors are naturally present in most forest areas but activated by stressors associated with temporary or chronic resource limitations.

Assessment of N- and C- forms and stocking within the rhizosphere. Garten's work identified various forms of organic material that are correlated with recovery and health in different soil types. These include soluble organic material (SOM), particulate organic material (POM), mixed organic material (MOM), and stable fine organic material (SFOM). Content and proportion of each reflect recent and past history as they are influenced by input and rhizosphere activity rates.

Once C- forms and conditions are assessed then nitrogen form and availability as well as its influence, through C:N ratios, on biological activity rates and mineralization of N via decomposition. Further characterization and documentation can be made by comparing soil N:P ratios with foliar N:P ratios. Because P is principally cycled through decomposition factors that would restrict mineralization but not N-fixation will result in elevated N:P ratios.

Biological activity rates such as rhizosphere enzyme concentration, microbial activity rates, N-fixation rates, etc. can be used to assess regulating processes that influence resource availability at different temporal and spatial scales, Again low availability of N can cause forest health stress and occur due to competitive deficit demands, limited N capacitance, disproportionate competing processes that result in loss of N from the system, limited mineralization, or limited input (N fixation).

Consideration of other rate limiting factors may be needed depending upon scale, condition, past-history, and perceived problem. Other “indicators” may include:

Availability of other nutrients such as P, K, Ca, and other basic cations or excessive amounts of compounds that reduce availability of these nutrients (e.g., Al).

Consideration of factors that influence establishment such as barriers to dispersion (seed movement, immigration, etc.) or reproductive success (e.g., pollination, tortoise hatchling survival, etc.).

Administrative recommendations

At present, Fort Benning should consider the following administrative recommendations to improve usefulness of a monitoring program as well as improve the efficiency of information transfer and implementation. Using general monitoring priorities and guidelines for successful monitoring, we recommend that the following administrative needs be considered.

Establish a sustainable, potentially shared, commitment and funding source for monitoring initiatives. This arrangement should consider compliance-type monitoring as well as monitoring criteria associated with long-term sustainability. The most suitable approach will be to develop cooperative arrangements with local organizations to develop mechanisms that will allow for financial leveraging and flexibility to accommodate the needs of unexpected planning (e.g., BRAC). These arrangements should also consider the possibility of 3rd party associations that allow for volunteer groups (e.g., Audubon society) to provide monitoring support with in kind compensation (e.g., vehicles, lunches). Strategic development of off-post partnerships can also be used to share knowledge and mitigate monitoring costs.

Develop and institute an integrated monitoring plan that describes methods and techniques that are currently, or may be potentially, deployed to assess the various environmental states and conditions. To improve applicability, a staff prioritized list of broad monitoring needs, goals, and objectives is needed. These priorities can then be implemented through a integrated monitoring effort. For example a list of priorities may include: a) terrestrial watershed assessment, b) progress toward DFC attainment, c) Upland forest health assessments, d) integrate on- and off-post landscape issues, e) evaluation of forest and range sustainability (ITAM), f) characterization of stream condition and water quality, g) evaluation of TER-S species status and habitat availability, h) Project level QA/QC, i) continued tracking of local weather and climate patterns, and so on. A multi-scale approach using tiered data coverages should perform multiple functions to address defined goals, and to allow for expansion of concepts and modeled expectations.

Develop a dedicated staff (including partnerships) that is focused on integrated involvement in identifying the critical questions and means of implementation to address these questions. Administratively, these individuals should collectively serve as a coordinating "umbrella" for research, monitoring, planning, and operational initiatives. This would include data convergence, integration, analysis, and product diffusion. To improve and facilitate usefulness to management and operations staff, the following addition positions may be needed:

Data integration, analysis for model development and summarization.

Remote sensing and GIS coverage development

Data management.

Develop a consistent POC for project integration that initiates letters of support for proposed work and documents concurrence with Fort Benning standards and protocol. We propose a two tiered system that would first involve an initial review of proposed activities and concurrence to support these activities by Fort Benning staff. This initial step would result in a support letter drafted by Fort Benning and would highlight issues of concern. When funded a second tier of protocol would be initiated and be focused on safety, access, project coordination, and data transfer to Fort Benning. These steps would lead to "sanctioned" research and improved coordination of activities as well as improved communication concerning project status. One necessary step would be that the funding agencies would need to state these requirements and conditions within the contracted arrangement and require documented concurrence by Fort Benning staff.

Future infrastructure support for research, contract, and monitoring activities should be considered. This support would focus on "term" visitor needs such as computer access for data entry and initial analysis, areas and equipment for sample processing (e.g., wet lab, dry lab), open bay office space, continued vehicle support, and arranged technical support. An improved means of entry access of authorized vehicles is also needed as well as improved non-citizen access to study sites.

Develop a better defined mechanism to implement monitoring results into resource planning and operational activities. To best achieve this, an administrative mechanism for information transfer that goes beyond diffusion from research staff to management staff. Therefore, a liason that has direct and identified roles in both programs is needed. The development of a stream lined approach to implement and test monitoring and research findings will improve the overall status of the environmental programs. The development of an improved approach would also better utilize the expertise of research, The Nature Conservancy, and other cooperators to directly address management issues.

Develop an annual monitoring report that describes the state and condition of monitored variables. This document, in unison with the monitoring plan, should be capable of providing enough general information that it could lead to specific questions from informed reviewers. This annual monitoring report would summarize the best available information concerning the status and state of environmental conditions and issues at Fort Benning and within the surrounding area. As an accompanying document, an integrated monitoring plan is also needed to describe the various objectives, techniques, and approaches. This document should be periodically updated and receive outside review, then be modified to best address monitoring objectives. This will allow for continued advancement in techniques and interpretation.

Implement improved record keeping is needed to represent military training activity. Currently, even with the best indicators, it would be difficult to suggest a relationship between a particular environmental problem and a land-use or training-use activity. Hence, the usefulness of the “indicator tools” is limited to simply identifying areas that may be headed toward an unrecoverable condition. For the most part without additional training information the resultant effective use will be limited to validating “visual gestalt” concerning the prioritization of which areas are in the greatest need of remediation, restoration, or rehabilitation.

If possible, develop better coverage and characterization of frequently applied information. An example, arrange for an improved soil classification at finer scales for "high traffic" areas. Initial soil pit locations should be reestablished and resampled; this information can be integrated and compared with that previously obtained during the initial soil classification. Comparisons will reveal the general extent of change since the previous evaluation.

Improved classification would lead to improved estimates of terrestrial water-use models; hence, result in better correlations with stream flow.

Improved soil classification would lead to improved soil-based silvicultural decisions; hence, improved habitat forecasting for TES species and improved long term forest health.

Summary of recommended monitoring actions:

Institute and develop an integrated monitoring plan that describes methods and techniques that are currently, or may be potentially, deployed to assess the various environmental states and conditions. Such a integrated monitoring plan should perform multiple functions (e.g., provide information to evaluate progress toward RCW recovery and the state of watershed conditions) and data should be tiered to multiple levels.

Develop an annual monitoring report that describes the state and condition of monitored variables. This document, in unison with the monitoring plan, should be capable of providing enough general information that it could lead to specific questions from informed reviewers. This annual monitoring report would summarize the best available information concerning the status and state of environmental conditions and issues at Fort Benning and within the surrounding area.

Improved record keeping is needed to represent military training activity. Currently, even with the best indicators, it would be difficult to suggest a relationship between a particular environmental problem and a land-use or training-use activity. Hence, the usefulness of the "indicator tools" is limited to simply identifying areas that may be headed toward an unrecoverable condition. For the most part without additional training information the resultant effective use will be limited to validating "visual gestalt" concerning the prioritization of which areas are in the greatest need of remediation, restoration, or rehabilitation.

Adapt tiered monitoring programs that tie project level evaluations with those at the installation level. This tie can come in the form of through the collection of common variables (qualitative, quantitative, inferred) at all sites and then through correlative relationships define the range and limits associated with each level of monitoring.

Develop an integrated qualitative matrix decision model that assesses the status of streams, watersheds, and acreages based on multiple criteria that range from weighted ordinational scores, projected biomass and productivity, and progress toward a DFC.

If all activities at Fort Benning were considered to be part of an on going “experiment” in which replicates were neglected (Bayesian experimental structures), and unequal and undefined responses were expect and inferred, it would be possible to construct a spatially and temporally hierarchical decision model that considers and equally weights all multi-scale data as well as decision-based “knowledge; “aka.” land management gestalt.” Templates for such a model exist and, in many ways, were the template for identifying potential opportunities to identify ecosystem indicators and thresholds. The litmus test for such a model would then be how it would be used and received by the regulating community. Such a “Bayesian” approach would basically make following assumptions a) sufficient information for a standard statistical approach will never be gathered, b) all of the gathered information was obtained with has finite, but unknown, variance that was partially, if not fully defined, by variations at other scales, and c) the collected data interdependent in a known manner and correlated across time and space.

Integrated monitoring should be deployed. We suggest four levels of varying intensity: a) installation wide, b) watershed/training area, c) stand level, and d) project level. A decision tree should be developed for each ecosystem health concern, with progressively more advanced, and deterministic, technique deployed based on observations of previous monitoring results. A similar program is used by the USDA-Forest Service concerning forest health issues (USDA-FS 2001). A decision tree to transition from watershed or training area level (e.g., forest classification and age from timber data base) to the stand level could be driven by a forest health issue (e.g., observed change in live crown ratio) or change in status (e.g., RCW colony establishment). Further, depending upon the reason for changes in monitoring, the additional implementation of monitoring is focused on the issue at hand (e.g., forest health = initiation of soil monitoring, RCW establishment = characterization of understory). The important factor is that information gained at each monitoring level has usefulness in interpreting information or deploying additional monitoring effort.

When possible, arrange for an improved soil classification at finer scales for “high traffic” areas. Initial soil pit locations should be reestablished and sampled, this information can be integrated and compared with that previously obtained during the initial soil classification. Comparisons will reveal the general extent of change since the previous evaluation.

Improved classification would lead to improved estimates of terrestrial water-use models; hence, result in better correlations with stream flow

Improved soil classification would lead to improved soil-based silvicultural decisions; hence, improved habitat forecasting for TES species and improved long term forest health.

Part III: Literature Cited and Useful References

9 Literature Cited & Useful References

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10 Evaluations of Parameters

Proposed terrestrial plot-level parameters

Soil A-horizon Depth and Soil Profile – **Relevance**: A-horizon depth reflects past land-use affects related to erosion and indirectly represent soil stability as well as site sustainability, productivity, and ecological potential. Because various soils at Fort Benning have natural differences in A-horizon depths (ranging from 5-60 cm), a more appropriate reference is surface horizon thickness or depth to “fines” (clay + silt) or depth to parent material (C-horizon). These definitions better reflect measures of soil loss because these metrics are composite to the initial soil condition. Soil profile and textural gradients similarly reflect these characteristics as well as drainage patterns, potential holding capacity and residence time. Though much of the information gathered by soil profile characterization can be obtained at broad general scales through GIS layers, which is sometimes sufficient for projects. Due to past land-use history, Fort Benning soils are seriously misclassified in some areas, particularly those with long training histories; therefore, to develop a general installation level understanding of the state and condition of the soils, and its dependent ecosystem, efforts should be made to advance the current monitoring program. Soil A-horizon depth, perhaps better termed surface horizon depths due to multiple horizons, was found to be directly affected by training, strongly affected by legacy conditions, and strongly influencing forest productivity. Whether historic or current, heavily used areas that are even slightly sloped are likely to have some displaced sediment resulting in thin surface horizons and exposure of sub-soil horizons. Further, severely disrupted soils often have migration of fine textured materials to deeper horizons where they collect to form a shallow impermeable layer, thus reducing water holding capacity. Other similar measures include depth to “fines,” whereby “fines” is defined as the summed percentages of clay and silt. Depth to parent material is sometimes used; however, within the sandhill physiographic region these measures can be quite deep; thus impractical to measure at intermediate scales. The importance of this simple metric can not be over stated because soil profile characteristics (depth, texture, structure) control local resource (water, nutrients) dynamics; which regulate productivity, thereby defining the ecological capacity and setting. Traditionally, silvicultural practices are strongly based on soil classification information; however, at Fort Benning many areas are sufficiently disturbed that the information associated with the *insitu* soil classifications are no longer representative of the existing soil conditions, hence, the relationship to various measures of forest productivity (e.g., site index) and recommended silvicultural treatments are not necessarily valid for some areas. Further, these same influences alter the setting and processes for the other proposed indicators; thus, these other indicators and associated thresholds will always partially reflect differences in the soil environment. **Recommended Methodology**: Soil A-horizon characteristics are best represented by 15-20 pooled samples. Samples can be extracted by various means, generally augers are used and characteristics measured upon extraction then sections of the soils can be segregated. The most typical errors occur when buried sediments are present (50+ years of "foxholes" at Fort Benning allows for a reasonable likelihood). **Monitoring Potential**: Measurements of A-horizon depth can be used to evaluate soil stability and estimate continued soil loss. As with measures of soil compaction and bulk density, generalized evaluations can be done in the field to validate mapped soil units, or in reference areas characterized by more intensive measures. **Labor and Cost**: Measurements of soil profile and texture can be made entirely in the field or involve some laboratory work. Generally, soil sampling can be coordinated with other biological sampling methods. Due to the high level of heterogeneity associated with Fort Benning soils, insufficient sampling is likely to occur if coupled with general forestry or wildlife management work. Depending upon topographic pattern, standardized methods call for 1-2 samples per acre in areas with low variance, 3-5 per acre for areas with intermediate variance, and 5-10 samples in areas with high natural variance. It is worth noting that a "sample" in this definition consists of 10-15 pooled soil cores. This work would be further complicated by the need for vertical stratification. Vertical classes can be defined by horizon characteristics (e.g., Oi 1-0 cm, A1 0-6 cm, A2 6-16 cm, B1 16-50, B2 50-76, C 76-120) or standardized depths (e.g., 0-5 cm, 5-20 cm, 20-40 cm, 40-80 cm, > 80 cm).

<u>Soil Moisture Conditions</u> – **Relevance**: Soil moisture conditions have chronic and acute affects on virtually all other ecosystem processes; therefore, direct and indirect affects need to be evaluated. Chronic affects result in ecosystem stress that results in reduced activity or productivity as well as capacity to respond to changing conditions, shorten life spans and persistence of diverse species and pathways, and higher incidence of pathogen attack. Acute affects regulate activity rates at all levels as well as result in the development of potentially lethal, hostile conditions. From a volumet-

ric and percentage basis, four moisture measurements are needed to evaluate moisture conditions; potential moisture capacity, amount present, amount available, and the flux into and out of the system. In the case of direct influence on tree growth these measures need to be estimated proportionally based on the root profile. In the case of chemical or bacterial activity, the evaluation needs to be made at the particulate or sub-cellular level. **Monitoring Potential**: Estimates of soil bulk density, soil texture, and percent organic matter are used to develop equations capable of estimating soil water holding capacity, estimates of water holding capacity can then be used to evaluate watershed holding capacitance and habitat potential. This information can also be used to define the relationships between soil water volume-water potential energies and in doing so, estimate drainage rates and storm capacitance for particular input conditions. Water volume can be estimated using "fresh" weight to dry weight relationships, and then with water potential equations used to calculate the amount available for at a particular water potential (e.g., warm season grasses = 2500-3500 KPa). With precipitation data, overtime these equations and types of information can be used to estimate the number of suitable growing season days for a particular species group. These equations can also be adjusted to represent parameter changes associated with land disturbance (soil bulk density, texture, %OM, A-horizon thickness), and then reused to evaluate the impact of habitat and vegetation. Water flux into and from the terrestrial systems can be estimated through estimates of precipitation, evapo-transpiration, percolation & drainage, storage capacity, and surface runoff rates as influenced by topography. Accurate estimates are difficult because most soil sampling disrupts soil structure which with the other mentioned parameters defines diffusion rates and patterns within the soil. **Labor and Cost:** These measurements are typically made with soil texture measurements, bulk density estimates, and other field techniques. These measurements would be necessary to develop an effective forest-hydrology model that encompasses the impact of changes in forest condition (health, land-use, productivity, type) on the recipient watershed and associated stream conditions. Therefore, if soils are assessed and monitored there would be minimal additional field cost.

<u>Soil Compaction, Surface Fracturing, & Soil bulk density</u> – **Relevance**: Soil compaction and surface soil fracturing are directly associated with mechanized equipment training. Both factors influence surface water drainage and sub-surface water movement patterns. Erosion and soil movement are collectively influenced by the two former conditions and of

particular concern near wetlands. Further, soil conditions (chemical, physical, biological) directly reflect the potential for long-term productivity and sustainability as well as define the breadth of future land-use opportunities at any given site. Soil density or compaction influences exchange rates (water, gas, heat, etc.) across the soil medium and with the soil surface. Denser soils have greater contact, thus are less capable of draining water or allowing gas exchange. Clayey soils are composed of tightly packed small charged particles; hence they tend to have higher soil bulk densities; however, highly structured sandy soils can have comparable bulk densities. As with soil profile and horizon characteristics, significant changes in soil density result in significant changes in moisture and nutrient status as well as the environment of the rhizosphere; hence, influencing the activity rates and the biotic composition and distribution within the rhizosphere. **Monitoring Potential**: Like soil profile and texture information, measures of soil compaction (bulk density) can be made in the field with a penetrometer, through the collection of a small sample of known volume, or, more accurately, through field precision methods. Like soil profile and texture, increasing disturbance through military training equates to increased surface and sub-surface soil disturbance; however, at the highest levels of disturbance, homogenization of soil profiles and characteristics eventually dominates the area and variance declines. At intermediate disturbance levels, areas adjacent to trees and along slopes have less indication of disturbance when compared to hilltops and open corridors. **Labor and Cost:** The equipment and labor needed to evaluate soil structure and compaction is generally low cost and can be obtained rapidly in the field. Techniques using penetrometers can be easily incorporated with other field sampling activities (FIA/FHM sampling, RCW matrix sampling, LCTA sampling, QA/QC project assessments, etc.). Univ. of Florida researchers proposed use of more exacting but labor- intensive techniques; however, in most cases, expected sampling frequency and scale would be inappropriate for this level of assessment.

Soil Erosion – **Relevance**: Measurement and determination in the amount and rate of soil movement within the uplands and into the riparian zone as well as the stream corridor. Two sources need to be tracked, bulk transport and surface transport. Both of these sources contribute differently to stream sediment amount, rates, and profile. **Monitoring Potential**: Two principal approaches can be used; a remote detection strategy, whereby accurate elevation measures are made to estimate fine scale elevation change between t_0 and t_1. These estimates can then cumulatively be combined for a given area. An alternative method is to use gaged pipe or tubing to detect surface and sub-surface change. This technique can be stratified across an area in question and then used to estimate collective change. Finally, at the wetland margin or stream, volume samples can be collected and, through extrapolation, used to represent a given area. **Labor and Cost**: Because erosion processes are cumulative and reliant on small-scale leading to watershed-level positive feedback processes, both a installation level approach using DEM (digital elevation measurement) data and a local sampling to characterize the rate of erosion activity in a particular area should be employed. Cost associated with DEM data can be high; however, when "piggybacked" with other aerial photography initiatives or acquired through satellite imagery, costs can be reasonably inexpensive. Local characterization of erosion problems can involve a period of intense sampling; however, this information is most valuable in prioritization of problems; hence, can save money in the long run. Finally, some effort should be made to periodically characterize sediment loss and movement associated with roadsides, paths, and other ROW corridors. As much as 90% of sediment movement is caused by these sources; hence should be characterized and used to evaluate potential mitigation procedures.

Soil Nitrogen – **Relevance**: Aspects of the terrestrial upland N budget are indicative of biological activity, which is directly related to the health and vigor of the ecosystem. Therefore, change in activity or process rates or soil N form and concentration provide indication that a change in biological activity or forest health has occurred. **Monitoring Potential**: Various measures of Nitrogen can be taken from stable transition points within aerobic and anaerobic pathways, the critical factor is to identify the rate limiting factor that influence various N form concentrations. These include measures of various compound concentrations, activity rates of regulating bacteria, measures of input and output, as well as various storage pools. Nitrogen mineralization, denitrification, nitrogen fixation, ammonification, and nitrification rates can be tracked based on bacteria activity comparisons with concentration levels. Soil pools of mineralized forms and organic concentrations can be tracked and compared with unavailable forms and concentrations in detritus. The difficulty in interpreting any or all of these parameters is the complexity of the nitrogen cycle. Further, nitrogen input, as well as many others, is facilitated by dry fall and wet fall deposition that is ameliorated by dust and fertilizer amendments associated with agricultural activities to the west. Perhaps the greatest limitation to using measures of soil nitrogen would be the variance associated with the values collected at Fort Benning, in many cases variance estimates were ten-fold, and often approaching hundred-fold, greater than the mean or median value. In most cases, these estimates are based on more than 100 samples. Using a modest value for probability estimates (p=0.90), several hundred samples, within the limited sampling area and setting used, would be required to satisfactorily indicate a significant trend or threshold. Hence, to develop some confidence in interpreting these values as indicators a much lower variance would be needed because the number of collected samples will always be limited. **Labor and Cost**: Nitrogen fractionation into nitrate, ammonium, and organic bound-N results in a cost of 22.00 $ per sample. A less expensive option is to analyze for total N (Keldjahl N) which reduces the cost to 8.00 $ per sample; though available forms such as nitrate and ammonium are discounted, estimates of total N is typically sufficient in evaluating nutrient status within upland forests; however, in severely or frequently disturbed areas whereby relationships between mineralization, N fixation, soil storage, and N plant uptake are impacted nitrate can accumulate and, because of high solubility, move toward wetland habitats. Typically, wetlands function as nutrient sinks; however, disturbed or ineffective riparian corridors could allow nitrate concentrations to reach water sources; whereby nitrate **could seasonally** affect water quality.

<u>Nitrogen Concentration in MOM</u> – **Relevance**: Nitrogen bound to Mineral-associated organic matter reflects site productivity, past and current land-use, and forest stability. These forms of nitrogen are also reflect available sources of N for future uptake. Successive disturbance or intense disturbance events reduce MOM-bound nitrogen through disproportionate relationships within the nitrogen cycle (Ex. excessive uptake coupled with limited N-fixation activity). In most terrestrial ecosystems, altered N-cycling processes are indicative of loss of sustainability and ecosystem stability. Therefore, monitoring of N can indicate future loss of forest character. Unlike measurements of total N, total organic N, MOM-N is well correlated with recent soil activity. It is worth noting that some method of tracking N dynamics may be worth consideration as it is relevant to water quality issues. It is generally considered that N loss to streams usually only occurs at levels of upland saturation, however, bulk transport of N through erosion or limited uptake of N through the loss of vegetation will result in the migration of into the riparian zone and allow for saturation and hence accelerated transition of DON, NO3, or NH4 into stream systems. Typically, healthy watersheds within eastern forests do not lose Nitrogen in any

form because it tends to be limiting. **Monitoring Potential**: To sample for MOM-N; an estimate of MOM (mixed organic material) is required; the sampling would require nested grids of sample collection from different soil depths. These samples would need to be pooled roughly 25 samples. Samples would need to be separated into 0-5 cm, 5-10 cm, and 10-20 cm. The number of sample collection points would be dependent upon the area being referenced and the collective complexity of soil profiles. Roughly 8-12 sample locations per acre would be needed for an intermediately disturbed area, this would include 5-10 pooled samples. A more homogenized setting (very disturbed or undisturbed) would require less samples, 3-5 per acre may be needed. Additional samples per acre would be needed if the surface soils varied from clay to sand within a represented unit. These additional samples would be needed to account for variability between samples; hence reduce the variability associated with concentration estimates for a referenced site. **Labor and Cost**: Excluding labor costs of collection and processing, analysis cost would be roughly $ 36.00 per sample (3 depths) or $ 108.00 per location, with an average recommended sampling density of 10 per acre, the resulting cost would be roughly 1080.00/acre. Labor cost this procedure, sample collection and processing, would be less than 2 hours/acre.

Nutrient Balance – **Relevance**: Within a moisture and light setting, nutrient availability at the time of need (bud break, flowering, seed set) is a critical component of plant community assemblage and productivity. Particularly influencial are balances and availabilities of macronutrients (N, P, S, K, Ca, Mg, Fe) as well as the chemical influences of other cations (Al) on availability. Because most of the soils associated with Fort Benning are inherently impoverished (silicaceous sand derived from sandstone within the rooting zone); most of the exchange capacity and storage is associated with organic residues. Further, differential loss of volatile and mobile nutrient forms following fire results in adjusted nutrient balance. For example, nitrogen tends to be limiting in fire prone areas, while phosphorus availability is limiting in unburnt areas. Generally, the effects of N loss through mobilization and volatilization is quickly minimized by N-fixation and atmospheric input. However other earth borne elements do not recover quickly without organic input. Cation limitation has also been directly linked to pine forest health problems. Though seldom used for reasons associated with cost, southern pine silviculture has long recognized the value of fertilization using “secondary” macro-nutrients (K, P, Ca). Compaction, thorugh the lack of gas exchange, also creates imbalances in nutrient availability. **Monitoring Potential:** In most cases, characterization and assessment of forest nutrient condition and cycling pattern is not needed; these assessments may be necessary in areas with poor growth performance or forest health. To evaluate nutrient setting; two approaches are used: soil collection within the rooting zone and foliage collection from the upper canopy. The former approach considers the content and balance of total and available nutrient forms, but discounts the influence of replentishment rates and uptake losses. The latter approach characterizes concentrations and proportions within the canopy which dominates the root profile. Therefore, multiple comparisons with healthy, productive stands can be made with unhealthy or unproductive stands, and comparisons of nutrient ratios can be made to between the soil and foliage. **Labor and Cost**: Dependent upon area, usually 3-5 soil samples from the upper 20 cm are collected. Similarly, foliage 3-5 foliage samples are collected, dried, ground, and stored. Traditionally, the soil samples would also be used for other soil analyses. Generally, preparatory steps are needed prior to analysis (e.g acid digestion). Analyisis usually involves spectroscopy (e.g., Technicon auto analyzer) or chemical emission characteristics (e.g., spark emission spectroscopy) to distringuish chemical composition. Macronutrient costs tend to range between $15.00-20.00 per sample, usually 20-30 samples are needed to characterize site specific problems.

<u>Tree Growth, Productivity, and Health</u> – **Relevance**: Productivity and growth are important components of forest health, development, and functioning. These measures are also good indicators in assessing compositional suitability and sustainability. Allocation of photosynthate typically follows the following order: (1) foliage and fine root replacement and growth, (2) primary growth of lateral and terminal roots and shoots, (3) secondary growth, and (4) reproductive effort. Obviously, allocation differs between species and allocation to secondary growth is sometimes proportionately last. Also, in stressed settings, allocation to reproductive effort is typically increased. These expected allocation patterns for individual species are typically used in assessing productivity and health (basal growth, root density, cone density, foliage density, branch density, foliage coloration, etc.). Monitoring secondary growth is a useful metric because it often reflects "real time" growing conditions and is useful in forecasting the need for future silvicultural activities. Generally, patterns of secondary growth are based on tree ring analysis or diameter increases during a set period (e.g., tree core assessment of 10 years of growth, diameter bands). Primary growth can be assessed by changes in tree height or rates of lat-

eral branch expansion in open forest settings or recently thinned areas. Foliage production can be monitored by collecting litter through out the growing season or through estimates of leaf area index (LAI). Finally, reproductive effort can be monitored by cone, acorn, or fruit production. Finally, remote imagery can be indirectly used to assess changes in crown coverage; these measures can also be made beneath the canopy using a hand held densiometer. Strategies for monitoring forest health are outline in the forest inventory & assessment/forest health protocol handbook; these techniques are comparable to those currently being used for permanent plots by TNC. **Monitoring Potential:** Generally, assessment of productivity and growth is restricted to particular areas with poor performance. Measures of forest health are collected as part of the RCW habitat matrix and as needed elsewhere. Though the techniques are very adaptable to standard forest inventories, most forest sampling designs do not include these measures. Dale et al. (2005) found that estimates of stand character did have some monitoring value in assessing the impacts of military training. These findings included all woody size classes, including understory components. **Labor and Cost**: These techniques are generally low cost, involve little additional sampling time and equipment cost. Unfortunately, with the exception of the RCW habitat matrix, the measured attributes do not address any current compliance issues; therefore, are generally excluded from forest inventory protocol.

Understory Biomass, Growth, and Productivity – **Relevance**: Understory conditions influence fire behavior, resource cycling, canopy productivity, habitat, and species richness. Therefore, some knowledge of these general features is important to management planning. Biomass estimation typically requires periodic resampling and development of allometric equations that allow diameter or density to be equated to biomass within different categorical classes (wood stem, twigs, leaves, fruit, etc.). Resampling is necessary to evaluate treatment recovery (burning, clip harvest, ground disturbance, etc.). One time spatial assessments using line-intercept or nested plot methods can also be used to evaluate patterns of coverage, biomass volumes, and exposed soil frequencies (see Collins et al. 2005). Productivity of herbaceous communities typically involves clip-plots whereby biomass is removed and then recollected after a set period of time. This approach allows for an accurate estimation of biomass growth. Similar approaches can be used to calculate litter accumulation, post-fire vegetative recovery, or herbicide effectiveness. **Monitoring Potential:** Generally, monitoring involving these methods is restricted to large, heavily disturbed areas; whereby recovery rates from buried seed reserves as well as native borne or dispersed seed is evaluated to determine if additional seeding is needed to reduce erosion risk. This approach is also used to evaluate fuel recovery patterns and rates, and its relationship to burn frequency. In the latter case, changes in fuel conditions and amounts can be equated to estimated smoke volume and particulate size. Over time, these evaluations may become increasingly necessary if air quality standards restrict the use of prescribed fire. **Labor and Cost**: Generally, the labor and cost of these evaluations are comparable to those used for biodiversity and plant community assessments. Accurate development of allometric equations from plot data is a labor intensive process, but once established these data and relationships can be extrapolated to predict conditions relative to fire behavior, habitat type and suitability, as well as forecasted fire or herbicide return frequencies that are necessary to maintain and improve DFC attainment.

Local and Landscape Patterns of Species Richness – **Relevance**: Patterns of species richness are indicative of ecosystem health, and reflect the attributes associated with functional efficiency as well as the capacity to withstand and recovery from disturbance. Overall species diversity and richness within a habitat and across a landscape are the most useful criteria for assessment, but diversity within important functional groups also provide insight. NRC(2000) recommended 3 metrics for species diversity, and each has applicability to the Fort Benning landscape. **Monitoring Potential:** Plant community data is currently being collected to evaluate other the biotic status of the Fort Benning landscape, therefore, these data should be initially used for assessing species richness patterns. Other biotic groups such as avifauna, herptofauna, small mammals, as well as terrestrial and aquatic invertebrate communities should also be considered. The availability of this information could allow for project level estimates of species diversity impacts and forecast potential species loss patterns associated with landscape change. **Labor and Cost**: For the most part, beyond the projected monitoring initiative no additional cost would be incurred by evaluating species diversity patterns. Some consideration of sample design is needed. Currently, four phases of assessment are or will be available at Fort Benning, these include; reference site monitoring, project level monitoring, species habitat monitoring, and the integration of research data.

Litter Quality and Amount – **Relevance**: Litter quality and amount reflects health and productivity of the litter source. Carbon-nutrient balances (e.g., C:N) for healthy plants are somewhat species or life form specific but because of the importance of foliage in productivity, small changes may signal noteworthy differences in resource allocation or health. Because of the importance of N in biochemical and physiological efficacy, C:N ratios are often emphasized in ecological assessments. Within the southeastern Coastal Plain, phosphorus is near equally conserved due to limited anion-exchange capacity, combustive loss in fire-prone areas, and slow, limited geochemical return cycles. Further, because of near optimal N-fixation and mineralization rates within the southeast, N supply is often only locally limited for short periods. It is also noteworthy litter comparisons be made between comparable sources. Fresh leaves vary seasonally and due to sorption prior to leaf fall differ in Carbon-nutrient balances from fresh litter, which due to solubility differences and selective removal, differ from seasonal leaf litter. **Monitoring Potential**: Typically 3-5 samples are needed to represent a particular condition (e.g., species at a particular site), with 3-5 species or conditions (e.g., fresh leaves, fresh litter, seasoned litter). Each sample typically includes characterizing litter type within 1 m^2 plots. Complexity in sampling (and the requirement for additional samples) is added by training intensity as well as diversity in composition (canopy, mid-story, shrub, forest floor) and forest structure. Because litter quantity and quality (flameability, carbon and nutrient content, amount) is strongly influenced by aboveground vegetation and disturbance history (e.g., training, fire, logging), nested vegetation plots to characterized conditions are often required. The most common sampling unit would be 1-3 acres, larger sites would require additional stratified sampling. Fresh leaves are best collected during the early portion of the annual life cycle (e.g., June), must be gathered as it falls and quickly collected to avoid loss of soluble nutrients. Seasoned litter is best collected during late winter, recent litter will have lost much of the readily available nutrients (N, P, K); hence be fairly stable. Further evaluation can be achieved through tracking C balances with structural nutrients such as Calcium (cell wall constituent). **Labor and Cost**: Generally, samples can be collected at a rate of 10-12 per hour with sample processing (weighing, drying, reweighing, grinding) taking a nearly equivalent period of time (10-12/hr). Analysis can be conducted using various techniques. An example would be Keldjahl digestion the analysis with a technicon auto-analyzer. The cost estimate for these techniques would be about 4.00 per hour if self conducted, 13.00 per sample if an outside lab performs the analysis.

Soil Organic Matter and Soil Carbon Concentration – **Relevance**: Soil Organic matter reflects past productivity and to some degree disturbance history. For most soils, Soil OM accounts for a significant portion of the resource-holding capacity; hence, directly reflects site productivity potential. The rate of conversion to alternative forms of OM can also be used to reflect soil health if consideration of other microsite conditions are taken. Total soil organic matter is correlated with total % carbon and various partitioned forms of organic material (COM, POM, MOM, Humus, SOM). The proportions and relationship between the various forms is noteworthy in interpreting recent vs. past productivity as well as the influence of disturbance. Soil Carbon Concentration discounts particulate SOM and focuses on elemental concentrations of carbon within the soil, exclusive of detritus compounds but inclusive of elemental C (charcoal from wood), non-organic mineral carbon compounds, as well as soluble and insoluble organic compounds. Thus, measurements of soil carbon concentration discount year-to-year differences created by burning as well as local-climate influenced processes such as decomposition rate and bacterial conversion of various organic carbon forms. Based on recommended soil sampling standards; chemical and physical soil attributes with some degree of confidence (p=0.10) can be represented by 3-5 samples per acre in fairly homogeneous soil settings, 5-7 per acre for intermediate settings, and 7-11 samples per acre for heterogeneous settings. Placement of soils should be in a stratified-random manner to provide adequate spatial and topographic representation. In separate analyses from a variety of sources, it has been determined that 10-15 soil sub-sample cores should be pooled for adequate sample representation. It is important to note that sample minimization and over consolidation (pooling) will result in adequate estimation of mean conditions but fail to identify potential "threshold" levels away the mean. **Monitoring Potential**: Estimates of total soil organic matter and carbon concentrations from mineral soil samples can be achieved using oven combustion methods. Tracking of soil organic matter is critical to most recovery models, is a critical predictor of the state and condition of a habitat as well as its water holding capacity, and can be easily incorporated into normal sampling protocol with soil surface analysis. **Labor and Cost**: Laboratory costs for combustion estimates of percent organic matter are typically low (5.00 $/sample), but the technique simply requires drying, weighing, combustion at 400^{o}C for 2 hr, then reweighing to calculate weight lost. Therefore, it would be recommended to perform this procedure "in house." Again, labor costs are highly dependent upon samples per acre, typically organic material is only assessed from the upper 0-10 cm, and occasionally the litter layer is collected and weighted (a separate technique).

Soil Rhizosphere Activity, Composition, and Genetic Diversity – **Relevance**: Microbial activity is indicative of current suitability conditions of the soil. Because of the high capacity of microbes to succeed into dormancy, representing activity rates can be difficult. Outside of seasonal and local weather conditions, factors that influence activity include compaction, moisture limitation, loss of suitable chemical material for activity, and general soil condition. Because of the potential for rapid changes in activity and composition, microbial activity best reflects the current condition. Relative to ecosystem function, microbial activity is the cornerstone process that regulates ecosystem process rates, all other higher order biotic processes are completely dependent upon the dynamics of the soil microbe community. **Monitoring Potential**: Though microbial and rhizosphere activity is indicative of ecosystem stress, the possibility of practical monitoring is limited by high rates of variance. Beyond diurnal variance, the highly heterogeneous soil setting and strong association of microbial activity with soil conditions is likely to result in the interpretive need for a large sample size, during a short period of time, across a reasonably small area. **Labor and Cost**: Sample collection and processing is more advanced than simple soil collection. However, soil sampling for moisture, texture, organic content, and nutrient balance is often needed to understand rhizosphere activity rates or concentrations of fungi, bacteria, or their bi-products. Analysis involves specialized equipment with some techniques requiring some period of incubation. These techniques may be cost-prohibitive for most monitoring settings because of the need for several samples, a series of replicates and duplicates, and reasonably high cost due to equipment and labor requirements. However, these techniques may be particularly useful in high disturbance settings that have limited response to rehabilitation efforts or those that pose significant threats as erosion sources.

Tree Density, Size, and Composition – **Relevance**: Tree Density reflects past histories of establishment, current affects of land-management activities, and is correlated with below canopy light availability as well as root competition. **Monitoring Potential**: At the stand level, tree densities are currently tallied using estimates by diameter class. Sampling involves standardized variable plot (prism) forestry techniques. These techniques are typically sufficient for evaluating mid-term stand growth progress. Other measurements of density and size are employed in RCW stands as well as to determine accurate estimates of timber volume within a given harvest area. The limitation to these methods is they are too infrequent (roughly 10 year periodicity) and coarse-grained (5-10 plots for a typical 40 acre stand) for detecting shifts in tree health and density that are related to training or management activities and these methods are poorly represent, and often overlook, densities of small mid-story and understory saplings. An important consideration is that certain methods favor certain aspects of distribution and size at different scales; however, merger of information from different methodologies and then analysis after log-normal conversion should be satisfactory to address most expected analyses. **Labor and Cost**: With stand exams, tree density can be estimated even when a dimensionless plot (point-quarter) or plotless (prism) sampling methods are used. Random, uniform, and clumped forest distributions have known patterns of occurrence and probability estimates can be made relative to individual tree size.

<u>Stand Age</u> – **Relevance**: Stand age and canopy type reflects past land-use decisions is directly associated with suitability for biota, particularly fauna. This parameter is currently assessed as part of the forest inventory and through assimilation of natural resource records. The relationship to identified DFC's as well as regulatory and stewardship responsibilities is direct. RCW recovery requirements have specific objectives concerning forest age and general type. These requirements are to provide RCW recruitment and colony establishment areas as well as foraging conditions. Briefly, older pine stands are beneficial to RCW recovery as well as watershed projection. **Monitoring Potential**: For even aged systems (e.g., planted upland pine), stand age can be easily estimated through stand establishment records as well as past and current tree core evaluations. Uneven aged systems are generally more difficult and often described based on size class characteristics. These methods are sufficient for planted plantations, but less affective for naturally established stands, uneven age stands, and pine-hardwood and hardwood stands that may be dominated by trees formed from sprouts. Further, stand ages are typically based on canopy-sized conifers and discount hardwoods; again, slow growing hardwoods and those formed from sprouts are often much older than pine cohorts. Also, some conifer species (Esp. loblolly pine) create “false-rings” which cause over-

estimates of stand age. The current method of assessment is probably sufficient for upland stand age estimate, particularly since the focus is toward conifer-dominated uplands. **Labor and Cost**: Generally no additional cost is incurred when traditional forest inventory assessment or common stand exam procedures are used. Further, the "birth" date of most young to intermediate forest ages are known through records.

Overstory cover and canopy openness – **Relevance**: Like stand age this reflects past land-use decisions and is directly associated with suitability for biota. Generally, indirect measures are used to estimate cover through calculations of basal area. However, at a constant basal area, the dispersion of gaps vary with tree size, thus indirect use of basal area to estimate understory habitat conditions, heat and smoke dispersion, or canopy interception of precipitation may be limited. Densiometers, convex-grid mirrors, are often used to assess canopy openness. More exact calculations, and permanent records, can be made using hemispherical photography. Another common use of overstory cover, or basal area, is to proportion forest conditions by species and then estimate relative ecosystem contribution based on these proportions. In most forests, dominant canopy species and soil conditions also define productivity levels, fire regimes, nutrient cycling patterns, moisture-use, and potential conditions for understory species. Additional emphasis is needed on quantifying in-place recruitment, sapling densities, and minor species composition. These parameters define suitability for additional species richness. Periodic assessments of changes in overstory cover and density can be used to assess patterns of forest health that may be directly related to land management or training activities. Changes in overstory cover can also indicate increased risk of soil loss, compaction, productive vigor, as well as lost resistance or resilience to disturbance. **Monitoring Potential**: Like stand age and density, overstory dominance is evaluated as part of the stand exam process. Again, the method is focused on evaluating the dominant condition and underestimates sub-ordinate conditions and species, which are often significantly important to stand level diversity. Nested plots to estimate woody understory cover and frequency of subordinate canopy species could be added to the current stand exam approach. Similarly, nested ground cover plots could be employed as well. **Labor and Cost**: Low equipment and labor costs relative to other procedures. Sampling is already conducted for various forestry and wildlife management reasons. Typically, when conducted for ecological reasons, overstory sampling is coordinated with nested understory sampling using well established field techniques. Often, information either directly related to resource conditions (e.g., availability of nutrients, moisture, below canopy light) or indirectly associated (soil conditions, topography, fire regime) are gathered as well. Challenges remain in extrapolating information from the sampling appropriate for land management decisions to those associated with watershed or local habitat dynamics.

Understory cover, composition, and life-form – **Relevance**: Plant families have family traits that reflect suitability of site conditions. Various SEMP and non-SEMP studies have identified species, families, and life forms that are sensitive to disturbance or specific to habitat characteristics (age, site condition, productivity, etc.). Relative to RCW recovery plans, understory composition and characteristics have become a targeted management condition. Further, understory type and quality greatly influences RCW diet and the ease of fire management, which influence RCW reproduction success. Most plant families have a common life form that exhibits these traits and conditions that favor one family over another are indicative of general conditions and subtle changes that alter the balance between family groups indicate collective change in site conditions. With knowledge that nearly all habitats have conditions that are best suited for a few particular life forms or families, patterns of life forms and family dominance can be used to indicate change. Departures from these conditions lead to other life forms making the most of their opportunities. The critical families identified for upland forest indicators include: poaceae, leguminosae, rosaceae, and asclepidaceae. The critical plant life form indicators include; therophyte, cryptophyte, hemicryptophyte, and chamaephyte. Collectively, unpredictable patterns of species occurrence limit the usefulness of single species understory indicators. SEMP studies indicate that therophytes (e.g., annuals) and cryptophytes (e.g., rhizomatous plants, growth tips beneath the soil) increase with disturbance; other species groups decline with disturbance. Collectively, some species and successional guilds, many described by others as far back as Odom (1950), were indicative of disturbance and forest age trends. Notable indicator species include; *Bulbostylis barbata, Cyperus croceus, Diodia teres, Aristida tuberculosa, Aristida purpurescens, Digitaria ciliaris, Andropogon virginicus, Dichanthelium spp., Sporobolus junceus, Pityopsis spp., Tridens flavus, Desmodium spp., Carex spp., Andropogon ternarius, Schizachyrium scoparium, Hieracium spp., Rubus spp.,Pteridium aquilium, Rhus copallina, Rhynchosia tomentosa, and Prunus spp.* **Monitoring Potential**: Current monitoring efforts to evaluate conditions for RCW recovery and Unique Ecological Areas

(UEA) have involved understory sampling of various intensities and forms. Traditionally, understory vegetation is monitored to evaluate responsive progress toward a desired goal or to evaluate the degradation of the landscape. SEMP studies, and others, indicate that disturbance patterns are best detected using life forms or family group. Using groups as opposed to species does not affect sampling protocols, but rather analysis after pooling of species. **Labor and Cost**: Sampling of understory vegetation involves greater effort by greater numbers of skilled individuals when compared to canopy sampling techniques. Because of greater capacity of establishment and shorter life spans that allow for more rapid competitive replacement, understory vegetation is much more responsive to changes of environmental setting and disturbance regime.

Faunal Groups and Species – **Relevance**: Often faunal groups are identified features of land management concerns and objectives. Vertebrate groups are also high profile indicators of ecosystem health or of special concern (e.g., gopher tortoise, migratory songbirds, overwintering resident birds, raptors, butterflies, herptofauna). Several new groups that are seemingly less charismatic (e.g., ant communities, beetles, dragonflies, toads, etc.) may be more effective at representing ecosystem conditions at appropriate time and space scales. Unlike many short-lived plant species, vertebrate communities represent a cumulative response to conditions at scales better suited to land management practices. Unfortunately, faunal populations are influenced by less well understood factors, so "build it and they will come" strategies sometimes fail for reasons beyond habitat management and quality. Unfortunately, the most cost efficient and predictably effective land management tool is habitat modification strategies. **Monitoring Potential**: Various means of monitoring faunal presence/absence, movements, and density exist and most involve remote sampling (e.g., capture, timed photography, call recording, etc.) or remote tracking. Though faunal sampling can be periodically labor intensive, sample designs and collection can often be coordinated with other land-use activities (e.g., military training). Statistically, faunal community sampling can sometimes be limited by lack of replications or representative conditions. Lack of sample replicates limit statistical inference and the uncertainty of representative data limit interpretation. **Labor and Cost**: These various techniques have differential costs due to differences in effort and scale; however, cost can be characterized into three categories: a) establishment and set-up, b) maintenance, and c) sampling. Over time, maintenance and equipment replacement costs eventually dominate cost profiles.

Landscape indices

Overall Relevance: The following is a list of traceable and commonly useful landscape parameters that can be evaluated using various imagery sources (visible light and IR photography, hyperspectral satellite imagery, LIDAR, etc.). These parameters are thought to influence migration within and between habitat patches. Obviously, some generalizations are made in using these estimates; namely what may be a habitat patch for one species is several habitat types for another or a sub-unit of a larger habitat matrix. Further, connectivity and isolation of patches is species defined; again what may be a barrier to seed or individual movement for one species may be a functioning corridor that facilitates genetic exchange for another. The most effective means of using these metrics is to define some a suite of species and conditions that reflect principal environmental issues. For example, tracking suitable habitat patches for a particular bird species that has a shared common habitat with a snake, plant, or insect. **Monitoring Potential**: Once patch types are defined and accepted as being representative or relevant to land management, then these measures can be periodically updated based on the observed change in habitat condition based on management activities. For example, during periods of little or no significant habitat change, existing habitat patch GIS layers are likely to represent for extended periods, during time frames of frequent habitat alteration, more frequent updates are needed for continued representation. It should be noted that with advancing technology and finer resolutions, “graininess” of the landscape inherently increases and the definition of “fragments” has higher resolution; therefore, evaluation of fragmentation, connectivity, patch size, etc. requires multiple scales that reflect the conditions responsive to multiple species groups. **Labor and Cost:** Typically, the maintenance and cost of updating imagery and GIS information associated with landscape monitoring becomes full time position(s). Depending on the source, type, and accuracy level of imagery greatly vary in cost. Often, the most accurate coverage is not necessary to meet particular management monitoring objectives; but more accurate historical coverage may be a necessary to adequately address questions associated with future monitoring needs.

Percent land cover – **Relevance**: The proportional abundance of habitat patches defines the relative proportions of potential species that could occupy the habitats. For example, at Fort Benning, independent of habitat quality or patch size, upland pine associated species are likely to be more frequent that upland hardwood species. Further, the most abundance habitat patch type has proportionately greater influence on the dynamics of the other patch types. Again as an example, fire prone, or adapted, habitats at Fort Benning are more abundant than fire adverse habitats; thus, their proportional abundance on the landscape increases the likelihood of a fire spreading into fire adverse habitat patches. Knowledge of the proportional abundance of habitats (cover types) is also useful in developing reasonable management expectations for species abundances and frequencies. Projected landcover change information can also be used to project local and installation wide impacts on species richness & diversity as well as vulnerability to invasive species establishment.

Perimeter to area ratios and patch-edge patterns – **Relevance**: Several ecological studies have found that some species optimize the use of transitional gradients and complex habitat transitions, while others require "interior" habitat conditions. The concept is that habitat "interiors" are less influenced by transitional affects and therefore exhibit more "predictable" habitat criteria. Many neo-tropical migratory birds are known to require contiguous habitat interior areas of a particular size or larger to meet their reproductive and home range conditions. Problems in generalization develop when you attempt to define "edge" vs. "interior" for multiple species because each individual species has its own set of criteria that define a unique range of optimal to inadequate conditions; these criteria and placement on the landscape then define influx/efflux rates of interacting source and sink populations. Finally, the "sharpness" of an edge (as depicted by collective change in ecosystem process rates, pathways, and patterns rate) varies between patch types and for particular patches. Several species are distributed along these transitions and the rate of transition is usually measured as beta-diversity. An example of a "sharp" patch transition at Fort Benning would be the transition from wetland communities to upland forest. Patch edge characteristics are partially unique to patch types and patch-to-patch combinations, therefore transition pattern somewhat reflects the stability of the landscape as well as patch sustainability.

Patch number and patch frequency – **Relevance**: The frequency and number of habitat patches within a particular distance defines the likelihood of dispersion between two patches as well as potential needs for connectivity. Again, how far an individual will migrate or a seed will effectively disperse is species dependent, but when on an individual species basis this information can be useful in identifying areas of potential future "bottlenecks" of dispersion. Further, identifying areas of high patch number and frequency can lead to management initiatives focused on creating cohesive matrices of congruent or complimentary habitat types.

Average patch size – **Relevance**: At the species level, the average size of habitat patches can be used to loosely define how many potential individuals or breeding groups could be potentially present if optimal habitat conditions were achieved. At the community level, habitat patch size reflects alpha diversity patterns and expectations which are positively associated with concepts of community resistance, resilience, and sustainability. All things being equal, larger patches are though to have greater stability because of greater number of companion species and potentially breeding individuals. However, from the stand point of conservation it is assumed that a mixture of patch sizes is needed to facilitate different levels of interaction, hence, gamma-diversity.

Range and variation of patch size – **Relevance**: The variation and range of habitat patch sizes often reflects the variation of possible conditions that might be expected within the patch. Local patterning, either due to inherent edaphic and topographic gradients or stochastic processes (e.g., light gaps), and the replication of pattern within the patch is related to variation of patch size. Further, the biological capacitance of a patch is size dependent because of the number and frequency of potential pattern combinations within the patch. Therefore a small patch with limited "unstable" patterning is somewhat restricted dynamics associated the limited number of species combinations that exist within the setting. Such settings are usually transitional, therefore vulnerable, to outside influence (e.g., establishment of invasive species).

Patch connectivity and distance – **Relevance**: Knowledge of patch connectivity is useful in evaluating the likelihood of the dispersion of a particular individual or condition (e.g., disease) to a neighboring set of patches. For some species, population isolation is also thought to restrict genetic exchange and reduce potential population growth. Various distance measures (Euclidean, Manhattan metric, logistic, real, etc.) between patches can be used to evaluate the connectivity of patches. The most appropriate scale that would be that which is best correlated with the pattern of target species or community response (e.g., genetic similarity). Further complexity is added when evaluating connectivity if inherent gradients or habitat patch shapes influence the directionality of potential dispersion of individuals or propogules.

Landscape distribution and pattern of patches – **Relevance**: In most cases, rhe distribution of patches varies with scale. At one scale patches may appear to be random at a larger scale the patches appear to be clumped into a particular section or location. The relevance is that these patterns influence how the components (e.g., populations) will interact and function at the landscape level. The distribution of habitat patches also influences management planning. A silly example would be do to the lack or limited occurrence, or limited potential for occurrence, of suitable patch types, RCW recovery at Fort Benning is not expected to include much of the Chattahoochee River floodplain. This influences land management and conservation branch direction, as well as work planning. Perhaps a more difficult task would be assessing the feasible occurrence of suitable patches for relict trillium populations within the Chattahoochee Valley sandhill region as to encourage some genetic exchange.

Patch constancy and variation **– Relevance:** Constancy of conditions and characteristics is critical to patch definition and identification**.** Variance within and between patch units is important for characterizing the quality and condition of each patch unit. Accuracy in characterization is necessary for developing strong linkages to existing and developing species habitat models. Further, these models need to directly characterize useage within identifiable habitat patch units. Finally, accurate characterization of patch constancy and variation is important for evaluating rates of transition to other well defined habitat units. These measures are helpful in defining beta-diversity measures across patch habitat units as well as alpha- and gamma-diversity measures.

Patch relevancy and transition over time and space **– Relevance:** From soil and topographic information they suite of types of expected vegetation can be estimated and the rate of transition approximated. These measures focus on the appropriateness of existing vegetation and how these types transition into other suites of expected vegetation types. These measures can be used to identify which landscape or stand units are most inappropriate for that setting and which transitions can be most improved by management actions. Generally, the use of these measures tends to focus "like" plant associations with other "like" associations and results in management actions that move away from proportioned expections within a management unit (e.g., each prescription unit should have Y% hardwood and X% openings, etc.). Often these measures are in conflict with traditional game management strategies because of soil- and topographically derived differences in landscape capability. These conditional expectations can be achieved at units larger or smaller than typical management planning units.

Stream and water quality indices

Dissolved organic carbon (DOC). Blackwater streams traditionally have high concentrations of stable humic acids and dissolved organic carbon. Declining levels of DOC and increasing levels of particulate organic matter (POM) is indicative of ineffective stream functioning, particularly benthos communities, or abnormal patterns of hydrologic flux. It is noteworthy that in assessing DOC levels, burning and associated runoff can have temporary influences on measurements.

Water pH. This parameter is reflective of suspended and dissolved organic and inorganic substrates. Again blackwater streams typically have acidic, nutrient poor conditions with low sediment loading. Coastal Plain streams that have slightly acidic to neutral pH conditions should be trigger further investigation. Historic land-abuse that has resulted in elevated suspended sediments (clays) are often responsible for increased water pH. However, calcic geologic substrates within the watersheds or extensive burning within the watershed (burning is an oxidation reaction) will result in a temporary increase in pH.

Dissolved oxygen (DO). Dissolved oxygen levels within streams reflect biological activity, water temperature, and mixing (flow). High levels of organic input can result in near anoxic conditions due to temporarily elevated respiration and biological oxygen demand (mostly due to elevated microbe decomposers within the benthos). Lack of flow can lead to reduced mixing and gas exchange rates as well as accumulating rates of respiration. Increasing temperature increases biological activity as well as redox reaction rates, both reduce net available oxygen within the water.

Nitrate concentrations. Nitrate concentrations are of human health concern because nitrate and nitrite are potential carcinogens and may cause birth defects. Luckily, in the southeast, streams have very low nitrate concentrations that are typically at or near detection limits. The reason for low concentrations are: (1) consistently high rainfall, (2) an extended period of terrestrial, wetland, and aquatic activity that allows for a prolonged period of active nutrient "conservation," (3) elevated temperatures elevate microbial activity rates that convert NO3- to alternative nitrogen forms and facilitate uptake and stabilization, and (4) ammonium is the dominant form of N within eastern forests. Therefore, because nitrate is generally indetectible, it may be a suitable candidate for monitoring because stream water detectibility may imply a loss in health. Further, local mineral soils typically have very low nitrate concentrations, thus, increases in nitrate would be unlikely to be due to erosive input (P or cation conc. Are much better candidates). Elevated stream water nitrate concentrations would therefore be due to either: (1) a decline in wetland or riparian functionality in conservation across transition boundaries, (2) a decline in nitrate conservation by stream biota/non-biota, or (3) a change in terrestrial input rates and sources due to reduced conservation, reduced "half-life" via reduced ecosystem pathway complexity, or increased source levels (manures, etc.).

Total suspended solids (TSS). Total suspended solids are inclusive of living and dead organic material as well as inorganics such as clay particles. In contrast to the Chattahoochee River, Fort Benning streams should have very low TSS and turbidity. Suspended and particulate organic matter are typically well conserved and an important constituent of the benthos community. These materials would normally be very low during base flow periods and then periodically "flushed" by storm events. Mineral suspended solids should be consistently low due to the terrestrial and wetland soil textures (limited clay concentrations); therefore, elevated sources are either derived from bulk erosion sources, particularly clayey sub-soils. Once within settled and deposited with bed sediments, impregnated suspended sediments are slowly released particularly during storm events; thus, suspended clays may be due to recent erosion or from buried sources caused by past erosion (19^{th} century farming, early military training, etc.). Through mineralogy differences, some potential of characterizing the source of TSS may exist and will be further investigated.

Inorganic suspended solids. This material would be the mineral sources of TSS. Included would be suspended clays and silt. Typically, blackwater streams have little or no inorganic suspended solids; therefore, elevated levels are an indicator of stream bed instability, erosive input, or bank erosion.

Inorganic Chemical Concentrations. Generally, black water streams are expected to have low inorganic suspended solids, particularly cations. Elevated anion (PO_4^{3-}, NO_3^-, SO_4^{3-}) levels are an indicator of either system saturation (unlikely in the SE US) or poor wetland health; therefore, anions and cations should be periodically evaluated during different seasons to assess concentrations and chemical balance.

Water concentrations of fecal coliform. Typically, cool, shaded, steadily-flowing streams have very low fecal coliform concentrations. Elevated fecal coliform levels are often an indicator of direct input, direct runoff from a terrestrial source, or loss of riparian zone effectiveness. Ratios and concentration forms can often be used to "divulge" likely potential sources. Once established, fecal coliform concentrations can be maintained or magnified through common growth (elevated temperature, etc.). When sources of fecal coliform are not apparent, other measure parameters (e.g., nitrate conc.) are needed to assess overall biological health of the stream. Further, when elevated levels of fecal coliform are detected, characterization of coliform type (e.g., human e-coli levels) and source is needed.

Stream water Phosphorus concentrations. Phosphorus has been identified as a rate limiting factor in many aquatic systems. In most systems P is tightly conserved; therefore elevated P concentrations are indicative of one of the following three conditions: (1) increased suspended or bound P (e.g., clay) from erosion sources, (2) increased flux, through reduced conservation, from the terrestrial watershed or (3) decreased stream ecosystem efficiency in processing input sources or conserving P in biomass. The first condition is most easily detectable through streamside evaluation of potential sources; further, this would also be accompanied by elevated levels of other nutrients and elements from terrestrial soil sources. Because of low anion exchange capacity and high sand content, the former condition could develop if a significant proportion of the landscape was without vegetation **and** the riparian zone was ineffective at capturing the increased loading of soluble P surface and subsurface runoff from terrestrial sources. The latter condition could develop through reduced biotic demand (reduced stream biota biomass), reduced biotic efficiency, or loss of food web complexity.

Stream temperature. Patterns of stream temperature reflect season, the amount of direct exposure to sun, and the collective temperature of runoff sources. Temperature influences reaction rate, oxygen level, and biological activity rates such as respiration. In most cases, slightly lower temperatures are better for vertebrate life forms due to greater availability of dissolved oxygen and lower benthic respiration and oxygen demand. Stream temperatures and flow rates are important parameters for detecting any future changes brought about by land use change or climate change. Therefore, some streams should be periodically monitored using automated devices.

Stream conductivity. Values of stream conductivity are influenced by charged concentrations of anions, cations, as well as suspended materials. Because various factors can result in changes in stream conductivity, this parameter is infrequently used as a critical component of monitoring programs. However, coincidently this variable is often needed to make accurate estimates within automated sampling devices; therefore is generally reported.

Stream water buffering capacity. This measure is indirectly a measure of ion concentration and conductivity as well as ion storage capacity associated with bed sediment characteristics. Because many unaccounted variables influence these estimates this measure is unlikely to be useful at Fort Benning. However, in areas concerned with heavy metal stabilization or in low rainfall areas (Western U.S.) buffering and storage capacity are important characteristics in evaluating stream health, stability, and capacity to withstand input.

Stream water turbidity. This measure is well correlated with TSS and may potentially be useful in remotely estimating TSS. Turbidity is influenced by TSS, particularly the inorganic fraction, but also influenced by the refractive characteristics of dissolved materials such as ions, organics (e.g., tannic acid). This is a critical metric because of risk associated with military training and compliance expectations for stream water quality.

Frequency, type, and amount of coarse woody debris (CWD). Due to the sandy nature of stream beds; biotic complexity is highly dependent upon stream meiofauna and macrofauna that efficiently utilize coarse woody debris material. Historic input of organics into stream systems are likely to have been through: (1) colluvial processes (e.g., spaghnum moss), (2) runoff of FOM, ash, and dissolved organic compounds derived from terrestrial fires, (3) foliar and twig input, and (4) input of large woody material through tree fall, etc.. Due to its size and consistency the latter source is a physical and chemically stable habitat setting that may also alter stream bottom characteristics through shift in water flow patterns or build of fine to coarse sediments behind the woody debris. Obviously, CWD performs multiple functions and elevated amounts should be expected to improve stream quality as well as provide additional resistance to catastrophic storm flow. ORNL/Auburn investigators found stream quality, biotic quality, and water quality to all be positively influenced by presence and frequency of CWD; but the persistence of individual CWD is greatly reduced by high erosion input or bed sediment instability. The CWD essentially becomes buried and once buried no longer contributes to invertebrate food web complexity.

Stream benthic particulate organic matter (BPOM). Like CWD, BPOM is an important energy source to stream biota and amount and diversity of source greatly influence meio- and marcro-invertebrate diversity. Accumulated BPOM is periodically lost during storm events. Flux of BPOM becomes an issue when turnover rates exceed the capacity for the establishment of biota to effectively contribute to efficient biological use of BPOM. Such a condition is mostly likely to develop in disturbed watersheds that support streams with very flashy, unstable hydrology.

Hydrologic patterns of base flow and storm flow. Nearly all of the above listed parameters are influenced by these measures. Its important to note that each stream has its own hydrologic behavior, particularly small streams that may have unique observed or unobserved watershed characteristics. Knowledge and predictive capacity of storm and base flow response of flow rate, water level, and volume allow for predictive effects on the other stream characteristics. Stream flashiness is a good indicator of water and stream quality and is best explained by contemporary land use patterns such as road infrastructure, percent open area, riparian health, etc.

Stream bed type diversity. This is a proportional measure of stream habitat frequency and is usually measured using a line-intercept method between two points along the stream channel. The bed sediment characterization, along with stream flow characteristics, is useful for estimated potential habitat of various stream species and guilds. The method generally characterizes by sediment type (e.g., muck, clay, sand, gravel, mixed, etc.) and local flow pattern (e.g., pool, riffle, run).

Stream bed stability. This is a measure of turnover rate of stream bed type as well as a measure of the rate of deposition or loss that leads to stream bed turnover, sediment bars, bed loss, or bed buildup. The easiest technique involves placement of “gaged” rebar with a washer and a weighted float. Net loss and addition through comparison of can then be made between two time intervals. At Fort Benning intense historic land use has led to higher levels of stream bed instability in some areas, stream bed instability reduces biological stability (particularly the benthos), which reduces the efficiency of biologic function, and then may be expressed as diminished water quality or diminished capacity to improve water quality. Stream bed stability can be improved through the placement of devices that adsorb water flow energies, convert from linear to laminar water flow, or consolidate unwanted sediment for periodic removal (e.g., sediment dams or pond catchments).

Streambank characteristics and stability. This is an indirect measure of the likelihood of bank sediment movement into the stream bed, and through storm flow activity, encorporation into the stream bed profile and suspended sediments within the stream. Unlike existing stream bed sediments, these tend to be “unwashed” and contain fine mineral soil that has the potential of becoming suspended sediments. The contribution of these sediments is dependent upon existing texture and the likelihood of eroding into the stream profile. The likelihood of erosion depends on stream flow pattern (e.g., flashy streams erose stream banks more readily than stable streams), existing root mass (bank roots retain sediment through resistance), and stream bank geometric characteristics (e.g., step angled banks are more erodible than shallow U-shaped stream banks). Particle size and soil density also influence the rate and likelihood of sediment movement and under cutting during storm flow events.

Stream biota

Algal activity rates

Seasonal measurements of algal activity cumulatively reflect temperature, sunlight, and stream chemical conditions that are necessary for supporting algal communities. In concept, algal activity rates, thereby algal biomass, should also influence future biological oxygen demand. Seasonal patterns of algal types and concentrations also reflect direct light exposure and stream temperature conditions.

Benthic macroinvertebrates

Macroinvertebrates are valuable indicators because the presence, abundance, and recurrence of particular species and species groups directly reflect carbon input as well as habitat setting. These species also regulate functional processes (e.g., processing coarse organic material) and are principal food web components. This group is a valuable indicator because they rapidly respond to changes in stream flow velocity, stream bed conditions, and stream chemistry.

EPT abundance. EPT measures represent collective counts of the number of taxa within the insect orders Ephemeroptera, Plecoptera or Tricoptera. This has proven to be a good indicator of stream quality at Fort Benning as well as elsewhere and is most influenced by historic land use. Therefore, this is a good metric to assess overall stream quality as influenced by past events.

Chironomidae species richness. Midge fly nymph diversity is maximized in streams that have some history of disturbance but an extended period of recovery. Elsewhere, most streams with high chironomidae diversity were once heavily used but have been allowed to recover since the early 20th century.

GA stream condition index (SCI) measurements vary seasonally and between streams, but are reasonably consistent from year to year. Index based on the product of weighted quality assessments for biological groups and their abundance.

Fish guilds and communities

Measures of small stream fish assemblages such as community composition and diversity are poor indicators of recent changes in disturbance patterns and but closely tied to historic land use because of its influence on collective habitat frequencies. Therefore, assessment of fish community characteristics is necessary to assess the initial “baseline” condition of stream segments and can be used to develop realistic expectations for those streams.

Fish Population metrics such as reproductive success, population age structure, and population density are good indicators of contemporary land-use because of its influence on habitat quality as well as seasonal patterns of food type, quantity, and quality.

To date, limited effort has been placed on large stream (e.g., Upatoi, Chattahoochee) assessments of fish communities. Several large stream indicators (e.g blue catfish, shortnose sturgeon) have been documented. Further, there is a direct tie to recreational opportunities and efforts elsewhere have shown that the health and quality of fish communities can be greatly improved through active habitat restoration (e.g., placement of CWD).

Bivalve populations, guilds, and communities

Water quality is greatly reflected by the type of filter feeding invertebrates present within a stream segment. Besides water quality (suspended and dissolved material) and the amount of suspended "food" material within the stream, the presence and types of species reflect the bed sediment type, stream flow characteristics, stability of habitat, and time since disturbance. The current limitation to using natural communities is due to a limited understanding of the complex biology and reproductive cycles of individual species particularly those which are rare. Some opportunity exists in using "fixed" filter feeding clams to evaluate cumulative water quality characteristics either through periodic bioassays for bioaccumulated chemical compounds or through assessments of survival rates of "fixed" filter feeders that are know to be sensitive to a particular aspect of water quality (e.g., sensitive to low BO, high turbidity, high TSS). Suitability for and occurrence of bivalves is a critical future need because of increased emphasis by USFWS as well as increased risk associated with within season and between year flux of water flow. These risks may be associated with changed land-use patterns and weather.

11 Proposed Fort Benning Monitoring Projects To Address Environmental Change Associated with BRAC-Related Activities

Using ecological indicators identified by the various SEMP projects, and others described in literature, the following monitoring programs are proposed for Fort Benning to address BRAC related environmental concerns. Planned increases in training load will impact environmental conditions at Fort Benning through increased training in existing training compartments as well as through the development of additional ranges and support facilities. These proposed projects are in addition to ongoing monitoring associated with TERS species management (RCW, *Trillium reliquum*, etc.) and other conservation and land management goals (e.g., restoration of the longleaf pine dominated open forest landscape). The proposed work will use recommended and accepted techniques as well as those developed through research at Fort Benning (e.g., SEMP, SERDP, CERL, etc.). Integration of field work will be through using GIS platforms and tied to remote sensing data. Using existing models that are based on ecological processes, the long-term goal of this program is to develop and provide integrated decision tools that consider various facets of environmental quality.

Watershed and stream systems – lead: Imm

The transition forest, including the wetlands, and stream processes regulate factors that control water quality and regulatory compliance; thus, training opportunity and capacity are indirectly influenced. Training impacts, and the potential for water quality degradation, are greatest at the small watershed scales in which impacts can still be mitigated. Critical factors include storm-water and base-flow hydrologic patterns, sediment movement, habitat character and condition, and chemical transfer efficiencies from the terrestrial landscape through the wetlands into stream water. Lost sustainability and efficiency elevates the risk of catastrophic loss of ecosystem services that protect water quality without interference with other Fort Benning missions. We propose to track the following objectives in six watersheds; each element is associated with a variety of regulations. Proper interpretation requires other background information such as landcover imagery, MET station information, and downstream water quality sampling. In order of priority, the monitoring objectives are:

- Project level stream characterization
- Stream profile and bed characterization (indirectly CWA)
- Stream bed and bank sediment composition and stability. (indirectly CWA)
- Stream hydrologic and turbidity profiles (indirectly CWA, state EPD TMDL)
- Project level impacts on stream biota
- Quality of stream biota using EPA & state recommended protocols. (state EPD regulations)
- Project related sediment input across riparian transition
- Surface and gully sediment movement rates along slopes and wetlands. (indirectly CWA)
- Project related changes in transition forest health, habitat quality, and connectivity
- Track changes in forest health, canopy cover, & canopy rainfall interception. (indirectly CWA)
- Using ecological indicators, track changes in habitat quality and invasive species occurrence. (PO 1306, NAMBA)
- Estimate of habitat fragmentation using changes in neotropical migratory bird breeding patterns. (NAMBA); correlate these observations to those observed using remote imagery data.
- Status of impacted TERS and conditions within selected Unique Ecological Areas adjacent to or within a BRAC-associated training area. (GA DNR)
- Project related changes in terrestrial carbon & nutrient budgets.

Using NIRS (remote imagery), detect change in chemical loading and transfer rates through the transition forest. NIRS estimates will be validated using collected soil estimates. (indirectly CWA)

Using vegetation data and allometric equations, calculated change in biomass (canopy, understory, ground cover, etc.) associated with construction and range use.

Because of access limitations and the involvement of areas without baseline information, it is necessary to establish this monitoring program prior to land clearing and construction. The primary risk of not conducting this monitoring is: (1) the occurrence of unobserved change that leads to costly mitigation to restore watershed services, (2) the long-term loss of training land sustainability and flexibility to meet future opportunities, and (3) elevated risk of non-compliance or regulatory action.

Water quality and hydrological monitoring – lead: Westbury

Army BRAC goals require the construction of new cantonment and training facilities to support the movement of the Armor School to Fort Benning. The mission will result in increased urbanization both within and outside of the Installation, new construction and land clearing activities, and significant changes to the present land use in order to fulfill the new training requirements.

Concurrently, the EPA is increasing it's regulatory authority in respect to impairment of streams due to non-point sources, such as increased stream sedimentation due to erosion. The regulatory assessment of this impairment is based on watershed models (EPA BASINS) that estimate sediment transport, and biological assessments using the EPA Rapid Biological Assessment Protocol (RBP).

As these regulatory requirements are being implemented, there is the risk that pre-BRAC conditions are not well documented, and that the effects of BRAC on stream health will be over-estimated. Current watershed models, such as BASINS, are largely based on remote sensing data. Research is underway at Fort Benning to improve this model's accuracy at estimating the effects of changing land use, particularly in regard to the effectiveness of the intact riparian zones, natural in-stream attenuation of sediments, construction best management plans (BMP), and restoration efforts. Another concern is that urbanization outside of the Installation will alter stream hydrology and increase sediment transport onto Fort Benning. All of these factors could lead regulators to conclude that new Installation activities have impaired stream health.

We propose to document pre-construction stream characteristics, particularly in regard to hydrology, sediment transport, and biology (RBP). This data will be used to support a BASINS model of Fort Benning and the surrounding area, and more importantly, allow the model to be tested and improved. Much of this work is underway, but there are data gaps that must be addressed. Currently, Fort Benning has twelve water monitoring/storm water sampling stations.

This proposal will establish staff gauges and develop stream discharge rating curves at these sites. In addition, 10 new sites will be established to monitor hydrology and turbidity (a surrogate for sediment transport), but not equipped to collect storm water samples. This proposal also includes funding for annual RBP studies of the resultant 25-30 locations. The product will be an Installation-wide data base, documenting pre-construction conditions, assuring the accuracy of the watershed model used by EPA, and monitoring the in-stream biological communities using the EPA RBP.

Monitoring BRAC-associated impacts on upland pine forest systems – lead: Addington

Upland pine forests provide nesting and foraging habitat for the federally endangered red-cockaded woodpecker (RCW) and numerous other rare animal and plant species on Fort Benning, and are thus a central focus of land management and conservation activities on Fort Benning. The estimated impact of the proposed BRAC/Transformation action on Fort Benning's RCW population includes loss of 32 managed clusters (out of 308) and loss of approximately 10% of the total foraging habitat (under the preferred Alternative B). In order for Fort Benning to meet RCW recovery requirements under the Endangered Species Act and Army Regulation 200-3, Fort Benning land managers must do more with less, i.e., through proper management techniques they must increase habitat quality so that fewer total acres are necessary to achieve recovery. Proper management techniques include prescribed fire, uneven-aged timber management, longleaf pine artificial regeneration, and control of invasive species, soil disturbance and erosion. Monitoring the results of these actions is necessary to determine if management objectives are being met, and if desired future ecosystem conditions are being achieved. We propose a permanent plot based monitoring program that addresses the following:

- Groundlayer vegetation and fuels monitoring – are objectives of Fort Benning's prescribed fire program being met and how do landscape patterns of fuel type and fuel load influence fire behavior and smoke emissions?
- Forest health monitoring – what is the extent and rate of pine mortality and how will this impact the installation's ability to recover RCW?
- Uneven-aged pine timber management – are RCW recovery guidelines for habitat structure being met by the installation's silvicultural operations?

- Invasive species status, occurrence, and expansion.
- Military and land management related habitat disturbance
- Integration with RCW population demographic monitoring and with landscape- and watershed-scale monitoring efforts

The primary risk of not conducting this monitoring includes inability to evaluate efficacy of management actions – whether habitat management goals are being met – and consequent inability to detect problems that may prevent RCW recovery. Inability to recover the RCW will lead to potential loss of mission capability due to resulting training restrictions.

Species and communities of conservation concern at Fort Benning – lead: Burton

Special-status species include species listed as threatened, endangered, or proposed as such by the USFWS, State of Georgia, and other species of conservation concern. The federal Endangered Species Act (ESA) protects federally listed, threatened, and endangered plant and animal species. State listed species are not protected under the federal ESA; however, they are protected under Georgia's Wildflower Preservation Act, Georgia's Endangered Wildlife Act and Alabama's Regulations for 2002-2003 on Game, Fish, and Fur Bearing Animals. Installations cooperate with state authorities in efforts to conserve these species. Other species of conservation concern include state species of special concern, rare species, unusual species, or a watch-list species. While not currently protected by the ESA, they could be considered for listing in the future and are afforded special management attention in Fort Bernning's INRMP.

Monitor species (plant and animal) of conservation concern

In BRAC affected areas, by MOU or contract monitor prioritized species of concern listed by the State of Georgia and/or Alabama. Monitoring will be conducted prior to and following construction to assess change in species population status, location, and condition.

Evaluation of Invasive species occurrence will be made using the existing plots from other monitoring initiatives.

Monitor conditions within Unique Ecological Areas (UEAs), particularly those most affected by BRAC actions.

Assess migratory birds via breeding bird counts and surveys in high priority areas (e.g., installation boundary and communication towers) - NAMBA, USFWS monitoring requirements

Though these species are good indicators of habitat and ecosystem health, forecasted tracking of these species and the relative impact of activities is important because periodic assessment and review (e.g., GA DNR) can lead to consideration for federal listing.

The condition and quality of these UEA may be suitable for translocation activities and habitat for species of concern such as the Gopher Tortoise.

Ecosystem monitoring – lead: Burton

An ecosystem monitoring approach is critical at Fort Benning as BRAC actions transform the installation in the coming years. Land cover maps (based on satellite and aerial imagery) and other remote sensing methods (e.g., hyper-spectral imaging) will be necessary to detect landscape changes that are a central component for monitoring and assessing change in other resources such as water quality, aquatic flora and fauna, terrestrial vertebrates, and vegetation communities. Land cover distribution is a critical description of the landscape, and may form the most obvious representation of the composition of resources within and outside the installation. Monitoring from remotely sensed data will be conducted at the regional (the entire USGS hydrologic unit 03130003), installation, and watershed scale (as defined by the watershed management units at Fort Benning) to assess changes in the environmental condition and resources that affect regulatory compliance thus affect military sustainability. Specifically, these objectives include:

Land use- land cover change

Assess change at the regional, installation, and watershed scale every two years

Landscape pattern

Assess critical connectivity and fragmentation metrics every two years

Justification/risk

This project will provide critical information for assessing other monitoring programs.

Disturbance, fragmentation, buffers, and land cover change are likely to affect the abundance of rare and endangered species (RCW etc), water quality, habitat quality, forest health, levels of biodiversity, and potential for invasion by exotic species. All are directly or indirectly related to various environmental compliance regulations and requirements (CWA, ESA, GA DNR, Carbon sequestration?).

Landscape information is critical for providing context of data sampled at points/plots and facilitates extrapolation of point/plot measurements across the landscape. This step is critical for predictive modeling and assessing "what if" scenarios for various resources which will become paramount for monitoring resources remotely as access becomes more restrictive.

Areas along the installation boundary are expected to experience encroachment which can minimize land inside the installation that can be used to support the installation's mission. This project will support Fort Benning's ACUB program (or similar program- wetland mitigation program) and will help identify priority conservation areas outside the installation.

12 White Papers

SERDP Ecosystem characterization and monitoring initiative

White paper C1.
Implementation of rapid bioassessment protocols (RBP) to characterize stream conditions at Fort Benning (Mark D. Farr, ECMI, Vickburg)

Introduction

Ecological conditions within a stream are often directly influenced by natural conditions or perturbation events occurring throughout a watershed. For this reason, streams have been referred to as “sentinels” of ecosystem health (Karr 1998) and often receive a great deal of focus when designing a long-term watershed monitoring plan. Training exercises and resource management practices at bases are often organized by land “compartments,” the boundaries for which often coincide with those of particular watersheds. A relatively simple multimetric approach, such as Rapid Bioassessment Protocols (RBP), can be used to evaluate potential impacts of training or environmental restoration on ecosystem health among watersheds at military bases.

Rapid Bioassessment Protocols were originally developed in the mid-1980’s as a cost-effective alternative to more intensive quantitative techniques used for investigating abiotic and biotic properties of “wadeable” streams (Plafkin et al. 1989). Subsequent refinement of RBPs has resulted in a relatively basic and flexible set of generally accepted methods for evaluating environmental, biological, and physical habitat characteristics of streams (Barbour et al. 1999). We implemented basic RBPs techniques to characterize and describe baseline ecological conditions at 32 sites from 23 1st to 5th order streams on Fort Benning Military Reservation (FBMR) during 2002-2005 (Figure 81; Table 31). Data also were collected from sites on larger non-wadeable streams (Upatoi and Uchee Creeks); results from these two larger systems are not included in this report.

As with many military training grounds, FBMR comprises live-fire ranges, troop movement exercises, catonement areas, large areas of unexploded ordinates (DUD), and other factors that can make design and implementation of a long-term monitoring program challenging. Limited access to some areas of the base during sampling periods as well as shifts in emphasis of objectives resulted in some sites being sampled less frequently than others since 2002. For this reason, results for this report are based on median site values.

Interestingly, much of the Fort Benning installation occupies a transitional zone between the lower Piedmont and upper Coastal Plain ecoregions comprising evergreen, deciduous, and mixed forests. For this reason, there are fundamental differences in stream characteristics across the base. At each 100m site, standard Rapid Bioassessment Protocol scores (Barbour et al. 1999) were used to characterize physical habitat quality. Environmental data describing pH, turbidity, conductivity, water temperature, and dissolved oxygen concentration also were collected to examine water quality conditions. Benthic macroinvertebrates were sampled at each site to indicate biological variability among streams. Data analysis indicated that four specific variables were particularly useful indicators of stream condition at Fort Benning: pH, RBP, HIBI, and %EPT. For each variable, we used median values from each sampling site to estimate conditions throughout the entire drainage. Based on this approach, our sampling sites represent approximately 58.3% of the base. Error in estimating conditions throughout an entire basin obviously can be correlated with basin size, sampling frequency, and other factors. Therefore we suggest conclusions based on these results be viewed as rough estimates of stream conditions at the installation. We also provide a brief summary of available Total Maximum Daily Loads (TMDL) information for base streams.

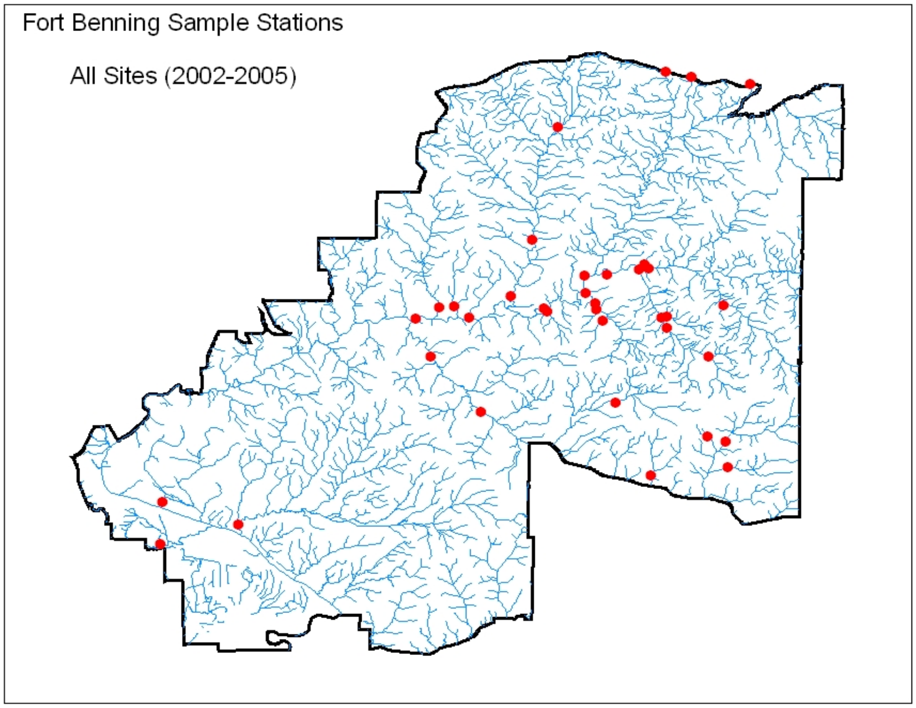

Figure 81. Stream sites sampled as part of the ECMI monitoring program at Fort Benning 2002-2005.

Table 31. Median estimates of environmental, physical, and biological factors describing stream conditions at Fort Benning Military Installation during 2002-2005.

Stream	PH	Conductivity	Turbidity	Temp	DO	RBP	HIBI	%EPT
		(uS/cm)	(NTU)	(°C)	(mg/L)			
Baker Cr	7.2	0.07	19.8	20.7	9.4	130	6.3	8
Bonham Cr	4.8	0.02	24.5	19.2	8.0	148	5.4	22
Cox Cr	7.0	0.09	13.0	21.8	7.4	173	5.1	10
Dstr Trib Bon Cr	5.2	0.02	2.8	19.6	6.5	156	5.2	27
Halaca Cr	5.4	0.04	17.5	17.6	8.2	143	6.5	3
Hollis Br	5.3	0.03	22.0	24.6	4.8	158	5.9	0
Hollis Cr	5.3	0.02	12.1	19.6	8.2	150	5.9	9
Hollis Cr Trib	5.1	0.02	12.0	20.8	7.8	165	5.1	5

Stream	PH	Conductivity	Turbidity	Temp	DO	RBP	HIBI	%EPT
Laundry Crk	5.6	0.06	3.7	16.2	8.5	148	5.3	30
Little Pine Knot	4.5	0.02	11.7	15.0	6.7	159	5.5	34
Long Br	5.3	0.02	7.5	22.0	8.6	152	5.2	15
Ochillee Cr	6.2	0.03	23.8	16.9	8.9	162	5.5	28
Oswitchee Cr	5.8	0.03	22.1	15.2	9.2	154	6.1	13
Pine Knot Cr	4.5	0.02	7.1	19.3	8.6	160	5.4	11
Randall Cr	7.2	0.06	10.0	21.6	8.6	118	5.7	49
Sally Br	4.8	0.03	14.0	16.1	7.3	146	5.9	6
Sally Br Trib	4.3	0.03	5.1	21.4	6.7	167	5.8	36
Tar Cr	7.4	0.10	24.0	21.7	9.1	115	5.8	9
Trib to Och Cr	6.1	0.05	19.5	17.3	9.3	137	6.1	7
Trib to PKC	6.1	0.02	6.3	19.8	6.4	147	6.5	9
Trib Upatio Cr	5.0	0.01	12.5	23.0	7.3	144	5.9	41
Upstr Trib Bon Cr	5.0	0.02	11.6	19.6	7.2	158	4.3	40
Wolf Cr	4.5	0.02	7.5	17.4	7.8	153	5.6	13

Environmental data (water quality)

pH - the rate at which enzyme-mediated biochemical reactions occur can be influenced by the pH of an organism's environment. Therefore, the range and variability of pH as well as the buffering capacity of the environment can affect overall habitat suitability for aquatic macroinvertebrates in streams.

Stream pH varies substantially among streams at Fort Benning depending on physiographic conditions. Although acidic conditions persist in most streams ($pH < 7.0$ in 79.8% of sampled basin area - SBA; Figure 82), streams in the upland portion of the base (e.g., Randall and Cox Creeks, Tar River) have pH greater than 7.0. Streams in the DMPRC portion of the base as well as Wolf Creek are very acidic (pH < 5.0) and represent ~26.9% SBA.

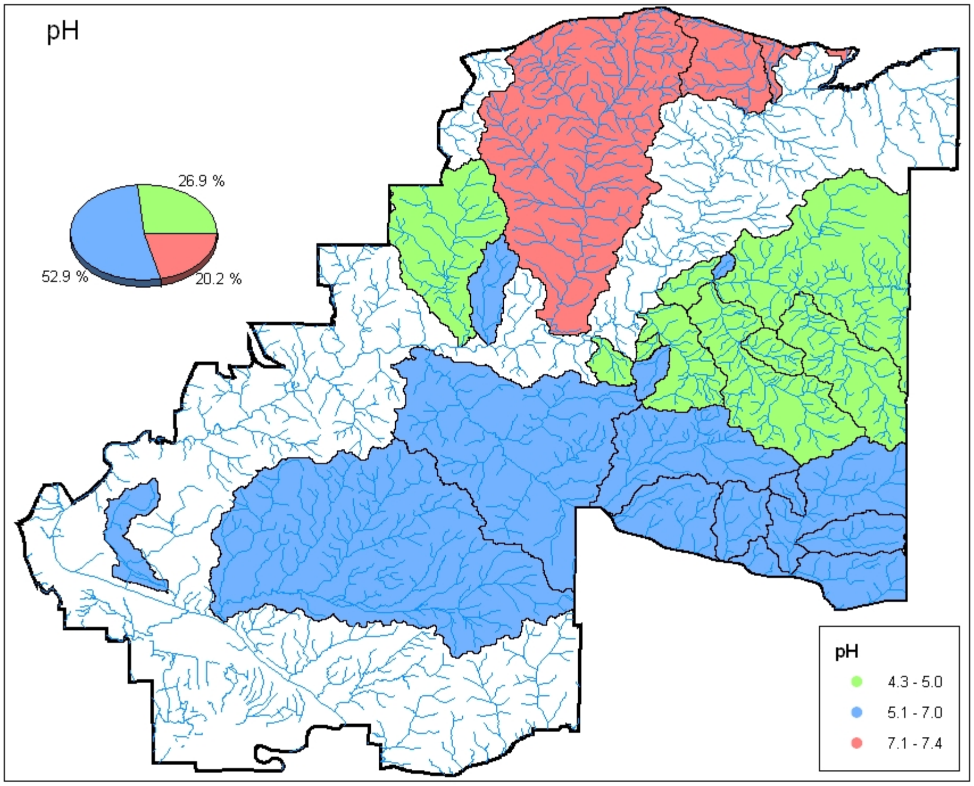

Figure 82. Estimated pH within sampled basins at Fort Benning, 2002-2005.

Conductivity – the ability for a current to pass through water is said to represent "conductivity" of a stream. The amount of dissolved inorganic particles within the water column determines how well an electrical charge is transmitted. For this reason, stream conductivity is most affected by local geological properties and tends to be greater in streams associated with clay soils rather than bedrock substrata. Conductivity also is usually correlated with pH yet can vary with temperature and turbidity (conductivity can increase with both temperature and turbidity).

Spatial trends in conductivity were, as expected, similar to those of pH (Figure 83). In general, streams with high pH (i.e., upland streams – Randall, Tar, Cox, Baker) also had the greatest conductivity measurements; these upland streams represented slightly greater than one-fifth of all sampled basin area.

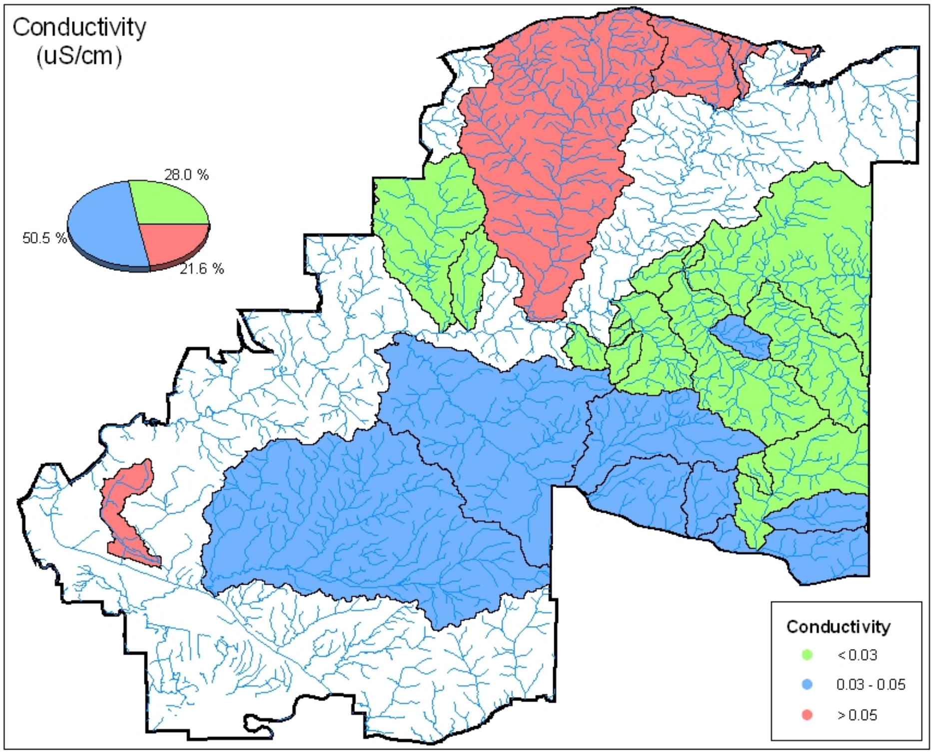

Figure 83. Conductivity (μS/cm) within sampled basins at Fort Benning, 2002-2005.

Turbidity – inorganic and organic particles suspended within the water column contribute to turbidity. Increases of turbidity are most often associated with runoff sediments carried overland into streams following rainfall events. Increased flow during precipitation events also causes resuspension of instream sediments. For this reason, any sources of erosion within a basin can lead to acute or chronic increases in turbidity and sedimentation. Small showers, animal crossings, etc...occurring upstream from sampling locations can result in misleading or variable estimates of turbidity.

Almost half SBA exceeded 17.3 NTU (nephelometric units), although most of these streams were in the lower portion of the base (e.g., Oswitchee, Ochillee, Bonham – Figure 84). Randall, Pine Knot, Wolf, and Laundry Creeks had relatively low turbidity (<10.1; ~ 35.9% SBA).

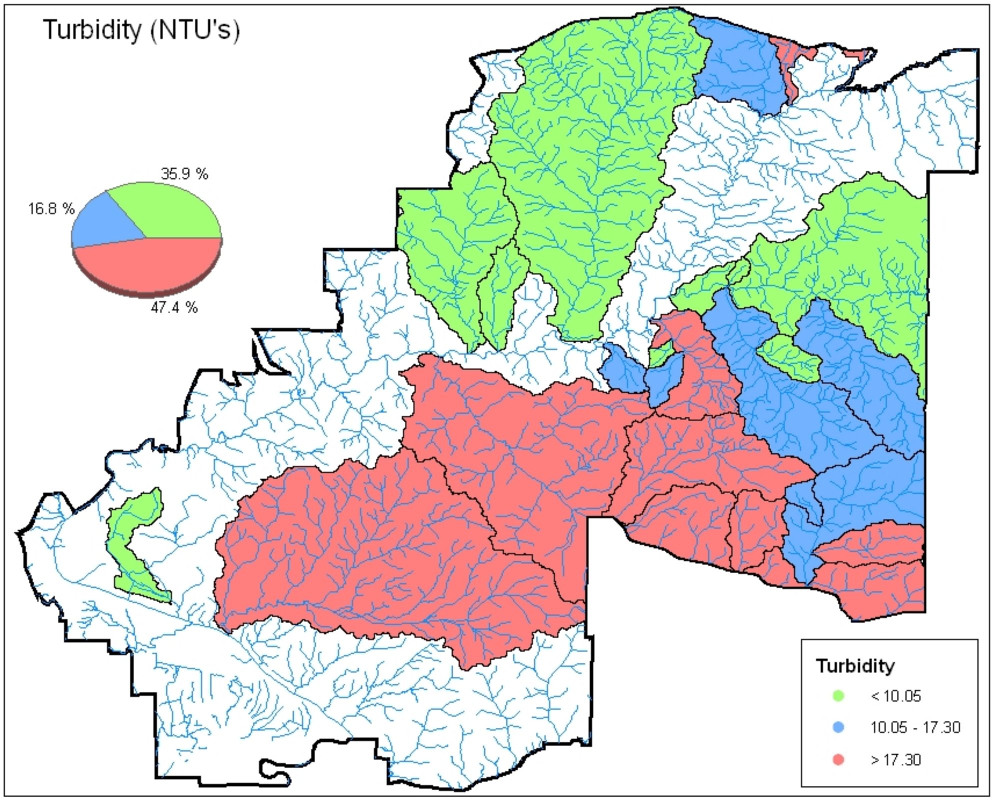

Figure 84. Turbidity (NTU) within sampled basins at Fort Benning, 2002-2005.

Water temperature – many biochemical processes in organisms as well as functional processes in ecosystems are regulated by temperature. In aquatic environments, water temperature affects rates of respiration, growth, production, and many other ecologically important factors. However water temperature can greatly vary diurnally, seasonally, with local weather patterns, atmospheric conditions, etc. Therefore the ability to use water temperature as a discriminating factor among streams at Fort Benning is limited. Although there may be actual differences among streams, single measurements made during annual sampling events only provide a very rough estimate of an overall temperature regime.

Water temperature varied substantially among streams at Fort Benning (15-25^{o} C; Figure 85). Streams in the uplands section of the base (Tar, Randall, Long, Cox Creek) generally were warmer than those in the coastal plain portion of the base. Streams with lower temperatures usually were larger, deeper streams less affected by daytime heating of shallow margins or smaller headwater streams with increased shading by canopy cover.

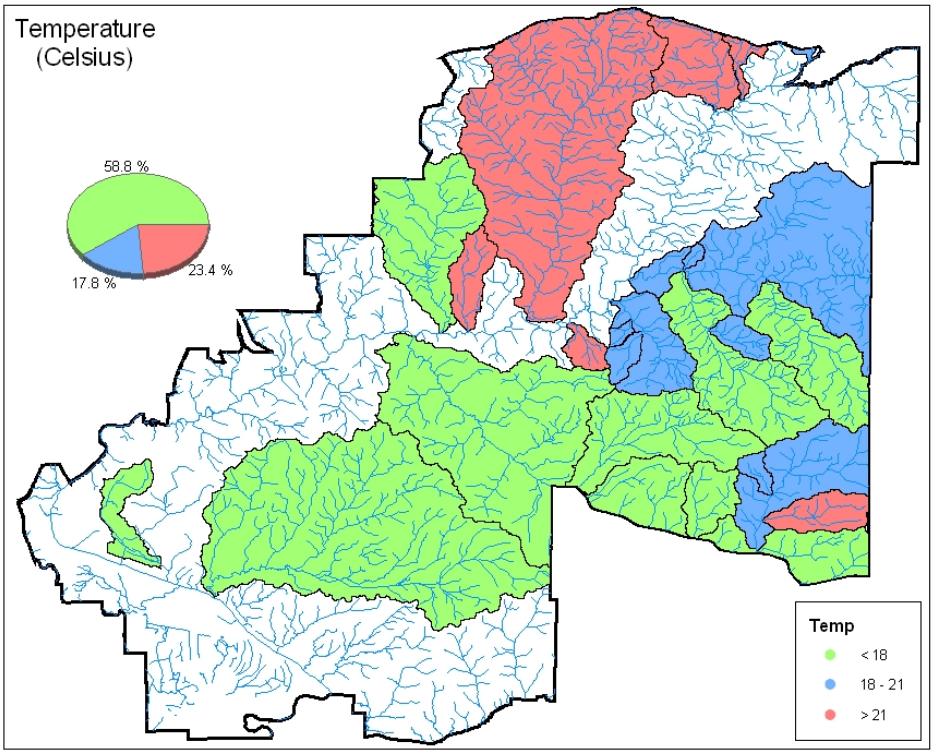

Figure 85. Water temperature (°C) within sampled basins at Fort Benning, 2002-2005.

Dissolved oxygen concentration – aquatic organisms require sufficient oxygen concentrations to allow underwater respiration through gills or absorption. Much like conductivity, turbidity, and temperature, DO estimates at a stream site can vary substantially during a twenty-four hour period. Low DO often is linked to dramatic mortality events in aquatic habitat (i.e., fish kills) which may be associated with pollution or elevated nutrient levels.

Over 93% SBA had median DO estimates greater than 7.0 mg/L (Figure 86). Of the other 5 streams, only Hollis Branch (DO ~ 4.85 mg/L) had a DO less than 6.0 mg/L.

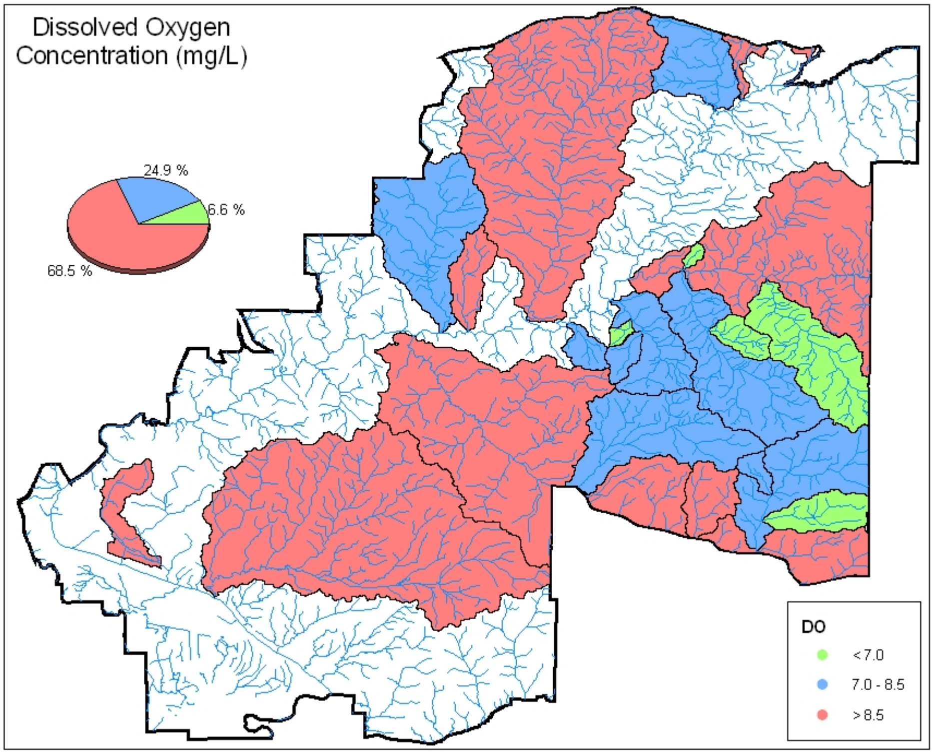

Figure 86. Dissolved oxygen concentration (DO mg/L) within sampled basins at Fort Benning, 2002-2005.

Physical Habitat Quality

Rapid Bioassessment Protocols - utilize a visual habitat assessment system where 10 habitat parameters are scored from 0-20 (0=very degraded; 20=pristine). Scores are then summed to calculate an index value reflecting overall habitat quality at a site. The 10 parameters include habitat features both within and outside of the stream channel:

Epifaunal substrate/ available cover – presence of substrate suitable for colonization by benthic macroinvertebrates and to provide cover for fishes

Pool substrate characterization – diversity and stability of pool substrata

Pool variability – abundance, size and depth diversity of pool habitats

Sediment deposition – evidence of sedimentation present within the channel

Channel flow status – proportion of channel submerged

Channel alteration – evidence of dredging or channelization

Channel sinuosity – degree to which the channel meanders

Bank stability – erosion along each bank

Vegetative protection – vegetative coverage along each bank

Riparian zone width – depth and development of the riparian zone

RBP scores indicated moderate (RBP = 130-149; ~16% SBA) to good (RBP >150; ~67% SBA) habitat quality among most sampled streams (Figure 87). Scores from two upland streams (Randall Creek and Tar River – RBP < 130; ~18% SBA) indicated relatively low habitat quality. These two systems can be characterized as shallow with very little depth diversity, almost devoid of instream stable substratum, and comprising a loose, shifting sand substratum. All of these conditions are considered indicative of poor stream habitat, although these conditions are not uncommon among upland sand-hills streams

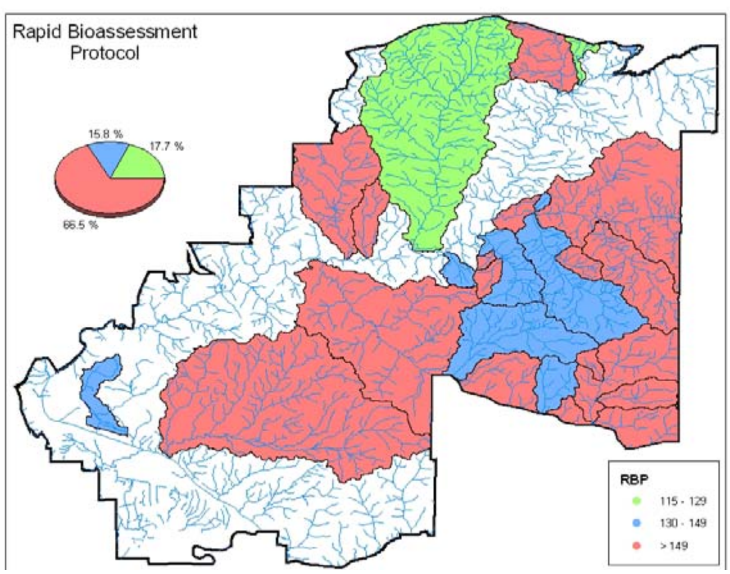

Figure 87. Estimated RBP (physical habitat quality) scores within sampled basins at Fort Benning, 2002-2005. Higher RBP scores indicate greater physical habitat conditions.

Biological indicators

Benthic macroinvertebrates are the most common group of organisms used for biological assessments in streams due to their ubiquitous nature, taxonomical diversity, and functional diversity (Merritt and Cummins 1996). Many ecological metrics and indices have been developed for using benthic macroinvertebrates to evaluate stream quality (Hilsenhoff 1988, Barbour et al. 1999). We used Hilsenhoff's Index of Biotic Integrity (HIBI) and Percent Ephemeroptera, Plecoptera, Trichoptera (%EPT) to indicate differences in biological characteristics among streams.

HIBI – Hilsenhoff's IBI estimates the cumulative environmental tolerance of macroinvertebrates sampled at each site. The resulting scores can range from 0-10 with low scores indicating a very low tolerance to environmental perturbation (good habitat quality).

Median HIBI estimates indicated moderate stream quality among most streams; estimates ranged from 5.1-6.0 for streams representing ~74% SAB (Figure 88). One stream, Bonham Creek, had a median HIBI estimate below 5.0 (4.3; ~0.5% SAB). Although streams with HIBI > 6.0 represented ~26% SAB, the largest basin in this group (Oswitchee Creek) was only sampled once and comprises streams draining a DUD area. Furthermore, no HIBI scores exceeded 7.0 or indicated "poor" habitat quality.

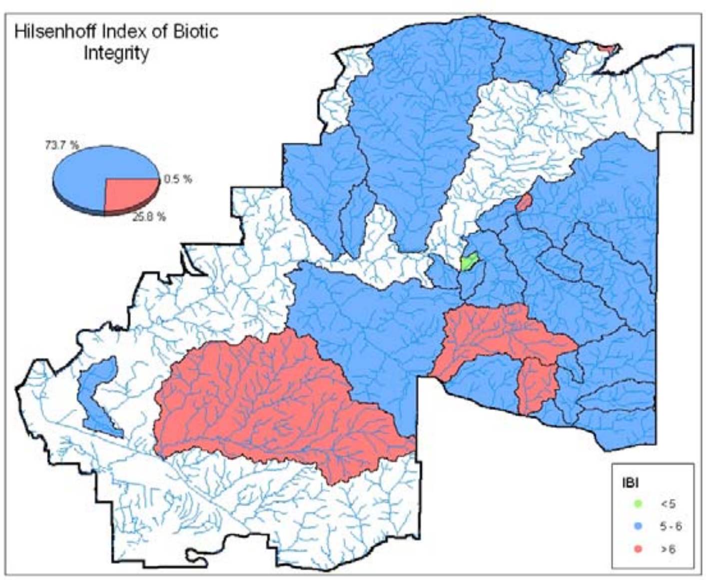

Figure 88. Estimated HIBI (Hilsenhoff Index of Biotic Integrity) scores within sampled basins at Fort Benning, 2002-2005. Low HIBI scores indicate greater stream quality.

%EPT – aquatic larvae of Ephemeroptera (mayfly), Trichoptera (caddis fly), and Plecoptera (stone fly) often are only associated with aquatic habitats of good quality. For this reason, the percentage of EPT organisms comprising the benthic macroinvertebrate assemblage can indicate overall habitat quality within a stream.

Median %EPT varied greatly among streams at Fort Benning (Table 31). Several streams contained fewer than 10% EPT organisms (i.e., Hollis Branch – 0%; Halaca Creek – 3%; Table 31), and over half SBA had %EPT less than 17% (Figure 89). Samples from other streams contained over 30% EPT organisms (i.e., Randall and Little Pine Knot; ~23% SBA - Figure 88, Table 31). However, more sampling will help determine whether these results reflect true variability in assemblage structure among streams.

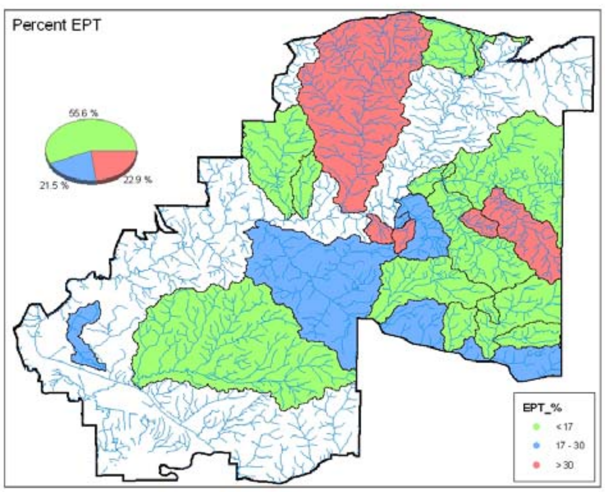

Figure 89. Percent EPT (Ephemeroptera, Plecoptera, and Trichoptera) within sampled basins at Fort Benning, 2002-2005; %EPT is often associated with better quality habitats.

Total Maximum Daily Load's (TMDL) for Fort Benning Military Reservation

The Clean Water Act of 1972 (CWA) set in place a means to monitor and regulate pollutants and discharges into the nation's waterways. Point source pollutants were the primary concern, however in since the 1980's, awareness has included non-point source pollutants. Sections 303(d) and 305(b) of the CWA set forth methods for states to monitor and report findings on the status of their waterways to the EPA. The primary method for reporting concentrations of pollutants is Total Maximum Daily Loads

(TMDL). TMDL's are the sum of all allowable pollutants into a stream from point and non-point sources as well as a margin of safety. TMDL's must be generated for each pollutant found in a waterbody allowing for seasonal differences.

Streams on Fort Benning Military Reservation have been sampled for possible pollutants. Those streams not meeting water quality standards in the past are: Tiger Creek, Little Juniper Creek, Pine Knot Creek, Little Pine Knot Creek, Hichitee Creek, Little Hichitee Creek and the Chattahoochee River. The Chattahoochee River is the only stream listed as not meeting water quality standards for pollutants other than sediment (biota and habitat impacted).

The Chattahoochee River section from the mouth of Upatoi Creek to the railroad at Omaha, GA (~50 km) is "Not Supporting TMDL limits for Fecal Coliform (FC) bacteria." However, possible point sources of FC at Fort Benning are apparently not responsible for this rating. The National Pollutant Discharge Elimination System (NPDES) permits two sewage treatment plants at Fort Benning allowing for a geometric mean FC count of 200 per 100 mL. Monitoring of FC at the effluents have resulted in a geometric mean of 8.1 and 6.7 FC.

Urban runoff is thought to be the cause of the "Not Supporting" listing for FC. Runoff from farms, construction sites, and other wet-weather sources occur in three basic manners: stormwater, combined sewer overflow (CSO) and sanitary sewer overflow (SSO). Combined sewer overflow can cause risks to human and aquatic life, aquatic habitats and the recreational use of U.S. waterways (US EPA, 1994). Fort Benning has initiated a Municipal Separate Storm Sewer System (MS4) plan to monitor and control surface runoff necessary under the Phase II NPDES Storm Water Runoff permit regulations.

The remaining listed streams at Fort Benning are impaired by sediments (biota and habitat impacted). Because they are Legacy sediments from previous land use practices no reduction is currently required.

Conclusions

Streams at Fort Benning are diverse in both habitat quality and condition. The confluence of multiple physiographic regions has resulted in both diverse chemical and physical habitat conditions among streams. Upland streams (e.g., Randall, Tar) are characterized as shallow, clear-flowing streams with very little pool development or instream stable substratum. Streams in the DMPRC portion of the base (e.g., Sally, Bonham, Little Pine Knot, Pine Knot) typically have very low pH but more depth diversity, variability in current velocity, and more stable substratum than the upland streams. Streams in the Ochillee drainage and most other areas in the southwestern portion of the base have moderately low pH with more diversity in depth and substratum; stable substratum and pool development is more prevalent in these streams.

Legacy effects from past landuse practices have influenced current conditions of Fort Benning streams. Although negative aspects of historical landuse may limit the upper limits of stream quality, the ECMI project has helped establish benchmarks upon which future changes in stream conditions can be compared. One of the longterm objectives of the program is to develop adaptive management tools to improve our understanding of how decisions can impact environments at the ecosystem level. The use of refined RBP methods along with the Georgia Department of Natural Resources IBI could result in the development of a system helpful for both: i) establishing current reference conditions (scores); and, ii) mitigating potential environmental quality impacts associated with resource management decisions at Fort Benning.

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SERDP Ecosystem Characterization and Monitoring Initiative

White paper C2: Analysis and application of Fort Benning meteorological station data (Donald W. Imm, PhD., University of Georgia)

Introduction

A major initiative of the Ecological Classification and Monitoring Initiative (ECMI) was to establish remotely positioned meteorological stations, and then integrate the information across the Fort Benning landscape. Ten MET stations were positioned across Fort Benning and intended to be representative of local weather patterns. The long-term focus was to integrate these stations with others across GA and the region.

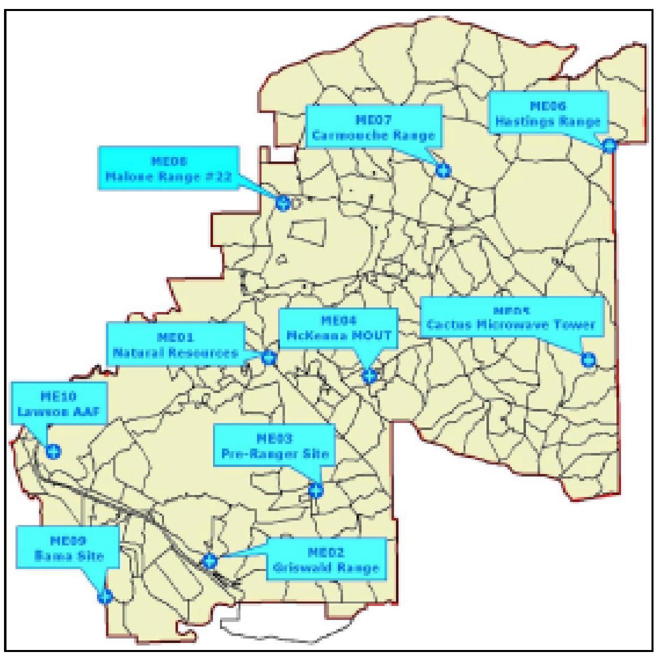

Figure 90. Meteorological station locations.

Analysis of weather station data

<u>Temperature relations</u>

Measurements of Fort Benning (FB) temperatures were strongly correlated with those from the Columbus Airport (CMAP). Linear regression models for daily minimum temperatures had an R^2 = 94.1% (Appendix 1) associated with the following equation:

$$\text{Daily MinAT}_{FB} = -0.388 + 0.9747\ \text{MinAT}_{CMAP.}$$

Similar results were found when daily maximum temperatures between the two locations were compared. The linear regression model representing daily maximum temperatures had an R^2 = 96.7% associated with the following equation:

$$\text{Daily MaxAT}_{FB} = 3.798 + 0.9497\ \text{MaxAT}_{CMAP.}$$

Because of these strong relationships, both equations could be used be used to project past temperature regimes for Fort Benning as well as future conditions. These same equations could also be used to other temperature related factors such at potential evapotranspiration (PET) rates.

Moisture relations

Unlike temperature information, precipitation patterns on Fort Benning and at the Columbus Airport were poorly correlated, R^2 = 45.1% (Appendix 1). Departures from a linear relationship were strongly expressed when precipitation associated with strong storms were compared. The linear regression equation between the two locations is:

$$\text{Daily Precip.}_{FB} = 0.0303 + 0.6260\ \text{Daily Precip.}_{CMAP}.$$

Seasonal differences in the strength of the linear relationship were compared, and correlational relationships were weakest during the summer months and only slightly improved during the winter months. Overall, because of the modeled relationship was significant, but less correlated than temperature due to strong storm event relationships. Though strong storm events are less frequent, they are disproportionately more significant when stream hydrology is of primary concern because a greater proportion of the precipitation is directly transferred to the stream as opposed to being intercepted by vegetation or stored in the upper soil horizons. Therefore, use of the linear equation is probably limited.

Using standardized precipitation indices (Appendix 2), station to station relationships, and those with off-Benning MET stations, are improved when seasonal intervals are considered (3 month). Standardized precipitation indices (SBI) are closely tied to measurements of the Palmer Drought Index, and require input from multiple MET stations from surrounding areas. With reasonable accuracy, the resulting linear regression relationships are suitable for predicting quarterly rainfall patterns on Fort Benning. Essentially, individual rainfall events are highly variable, but precipitation patterns equilibrate over 3 month time periods.

In many cases, these stations are nearby one another or at similar elevation and contour positions (Table 32). Nearby stations would be expected to have similar precipitation patterns and in some cases was true. Comparison of correlations of monthly precipitation data (2001-2007) between MET stations reveals that many stations are highly correlated (Table 33). Similar correlations exist for other precipitation time periods.

Table 32. **Distance between MET stations (Km)**

	NR office	griswald	pre-ranger	mckenna	Cactus	Hastings	Carmouche	Malone	Bama	Lawson AAF
NR office	0.0	11.6	7.6	5.5	17.8	22.5	14.4	8.9	16.1	13.7
griswald	11.6	0.0	7.1	13.6	24.0	32.3	25.4	20.4	6.2	10.1
pre-ranger	7.6	7.1	0.0	7.0	16.9	25.4	19.2	16.1	13.3	14.8
mckenna	5.5	13.6	7.0	0.0	12.4	18.7	12.2	10.8	19.3	18.5
Cactus	17.8	24.0	16.9	12.4	0.0	12.1	13.4	19.3	30.2	30.7
Hastings	22.5	32.3	25.4	18.7	12.1	0.0	9.5	18.6	37.9	36.1
Carmouche	14.4	25.4	19.2	12.2	13.4	9.5	0.0	9.2	30.4	27.6
Malone	8.9	20.4	16.1	10.8	19.3	18.6	9.2	0.0	24.1	19.7
Bama	16.1	6.2	13.3	19.3	30.2	37.9	30.4	24.1	0.0	7.6
Lawson AAF	13.7	10.1	14.8	18.5	30.7	36.1	27.6	19.7	7.6	0.0

Table 33. Monthly precipitation pearson-product moment correlations.

	NR office	griswald	pre-ranger	mckenna	Cactus	Hastings	Carmouche	Malone	Bama	Lawson
Station#	1	2	3	4	5	6	7	8	9	10
NR office	1.00	0.80	0.86	0.85	0.83	0.68	0.79	0.85	0.83	0.81
Griswald	0.80	1.00	0.87	0.80	0.86	0.73	0.79	0.71	0.83	0.76
pre-ranger	0.86	0.87	1.00	0.82	0.85	0.70	0.82	0.71	0.87	0.76
Mckenna	0.85	0.80	0.82	1.00	0.77	0.66	0.81	0.71	0.84	0.71
Cactus	0.83	0.86	0.85	0.77	1.00	0.79	0.86	0.68	0.84	0.74
Hastings	0.68	0.73	0.70	0.66	0.79	1.00	0.75	0.59	0.71	0.69
Carmouche	0.79	0.79	0.82	0.81	0.86	0.75	1.00	0.61	0.93	0.61
Malone	0.85	0.71	0.71	0.71	0.68	0.59	0.61	1.00	0.62	0.68
Bama	0.83	0.83	0.87	0.84	0.84	0.71	0.93	0.62	1.00	0.73
Lawson AAF	0.81	0.76	0.76	0.71	0.74	0.69	0.61	0.68	0.73	1.00

Using hierarchical, agglomerative clustering of the collective correlations associated between the 10 MET stations results the relationship between MET stations shown in Figure 91.

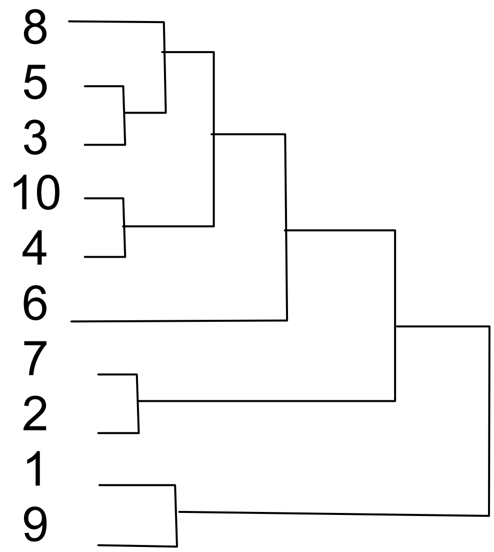

Figure 91. Relationship between MET stations.

The most strongly correlated stations are McKenna MOUT (4) and Lawson Army Air Field (10), the pre-ranger site (3) and Cactus Road (5), and those MET stations at Griswald (2) and Carmouche (7) Ranges. Again, these strongly correlated sites are not necessarily nearby stations. The weather stations at the Natural Resources Office (1) and the Alabama Site (9) are also strongly similar, relatively distant from one another, and both have precipitation patterns least like the other MET stations. This information can be used to identify redundant MET stations or to develop regressional relationships between stations that could then be used if a particular MET station was repositioned to a new location.

Application of weather station data

Once technological limitations are worked out, the MET stations will be linked with the existing GA network. Regional connections of MET stations can be used to improve atmospheric models such as those used to project smoke dispersion and plume behavior as well as local night time temperature inversion patterns.

These data are required for ongoing research involving watershed modeling (BASINS) as well as C- and N-cycling models (CENTURY-model based). Once developed and validated, this will be used for Fort Benning monitoring, these models allow for installation-scale estimates of carbon and nitrogen turnover, retention, and balance. The BASINS model will allow for evaluations of individual stream watersheds. Based on data and observation, some Fort Benning streams are more influenced by precipitation patterns and terrestrial water-use processes than others. Therefore, some streams would be more influenced by, or responsive to, land-use change than those which receive higher relative input from ground-water fed springs. In constrast, spring-fed streams should be evaluated using different parameters, such as off-post ground water dynamics or long term surface water-ground water flux. From a land management perspective, project-level hydrologic concerns and decisions should favor focus on those streams more strongly influenced by surface-water input patterns.

Several other models are highly reliant on accurate weather data, these include forest growth and health models as well as those that depict ecosystem dynamics (e.g., LINKAGES). With potential impacts of climate change, this information will also be valuable in projecting habitat change using ecosystem process models such as CENTURY, LINKAGES, JABOWA, etc. Tracking climate change may be particularly important at military installations because of the frequency and types of disturbance that may lead to earlier response of biotic communities to climate change through higher stress and lower resilience.

Independent of the BASINS modeling effort, MET station data is currently used to correlate hydrologic pattern, sediment movement, and stream turbidity. These factors are collectively used in monitoring stream conditions and biotic quality (e.g., RBP). Other research studies also continue to use MET station data (e.g ORNL DMPRC study).

Recommended considerations

Because of highly correlated temperature patterns and strong correlations of precipitation between some MET stations, the number of MET stations could be reduced to seven and still have comparable weather pattern coverage. Independent of access and logistics, the least valuable MET station sites are those at the Natural Resources office, pre-ranger site, and cactus microwave tower. In the short term, the needs for the BASINS model should also be considered. Continued efforts to link these weather stations should also be made because of local and regional concerns over smoke dispersion and air quality. If improved assessment of precipitation patterns are needed, an additional 15-20 automated rain gauges could be deployed within a particular watershed or across the installation. This may be necessary if local erosion risks are greatly elevated; this may be the case in some BRAC-related construction areas.

As MET station units are replaced, additional sensors should be considered. Sensors to monitor soil moisture and soil temperature would be useful for monitoring drought, fire planning, and developing estimates of soil moisture storage. These sensors should be placed in open areas and beneath a nearby forest canopy. Similarly, sensors for fuel moisture estimates should also be deployed to represent different fuel types. With KBDI, these estimates can be used for prescribed fire planning, and assessing the advancement and risk associated with wildfires. Again, sensors should be placed in open areas and beneath nearby forest canopies. Other additional sensors could include air quality and lightning strike sensors. Both could have value in tracking air quality and safety risk.

SERDP ecosystem characterization and monitoring initiative

White paper C3: Summary and application of landcover and trend analysis (Donald W. Imm, PhD., University of Georgia)

Comparison of the Landsat ETM+ coverages for Fort Benning and within the HUC unit associated with Fort Benning and Columbus-area streams requires a brief explanation of differences and advancement in technique. Except when noted, the coverage boundary, and associated area, has not changed. Between the period of 2000 and 2007, a land exchange occurred between Fort Benning and the city of Columbus; therefore, the boundary of Fort Benning changed during this period for the most part these areas were dominated by planted and natural upland pine forest.

The initial coverage did not initially include an impounded portion of the Chatahoochee River that encompasses River Bend State Park; therefore, water estimates for on- and off-post open water area differs between Landsat coverages from 2000, 2003, and 2007. The River Bend SP area is referred to as “Not Mapped” Fort Benning Hectares. The relative amount of open water has remained fairly constant during the period of this study.

Off-post urban interface hectares were not initially classified in 2000; this area was likely dominated to by urban land cover with lesser percentages of forest, scrub/shrub, bare ground, paved roads, and herbaceous land cover types. Also, the land exchange led to some cantonment area being included within the non-Benning land cover classes.

To reduce classification error and increase interpretation, the 2003 land cover type classification began to class evergreen/hardwood forest areas separately. This forested component in the 2000 land cover type classification was likely to have included in natural evergreen, hardwood, and scrub/shrub categories.

To reduce classification error associated with recently burnt areas, the 2007 land cover type classification included a recently burn cover type. Considering the locations, the area included as recently burnt are likely to be natural pine, scrub/shrub, herbaceous, and lesser amounts of hardwood land cover types.

Table 34. Landcover types, Fort Benning environs.

Landcover Type	Fort Benning (Ha)				Non-Benning (Ha)		
	2000	2003	2007		2000	2003	2007
Water	714	1031	1120		1235	1556	1870
Hardwood	26056	22023	19259		33193	26082	19350
Evergreen/Hardwood	-	17343	19241		-	12255	14355
Scrub/Shrub	9227	5759	6254		12671	12946	12308
Planted Evergreen	3801	1988	798		13094	12103	12036
Natural Evergreen	19721	14893	11930		5621	15795	17474
Burn Area	-	-	2733		-	-	802
Herbaceous	6206	3302	2019		19818	9538	8183
Bare Ground	1332	1392	4107		942	3534	7042
Paved Roads	1300	766	1053		2176	2117	2000
Cantonment	5426	5426	5206		0	0	32
Urban	-	0	0		-	11753	12240
Not Mapped	585	-	-		17522	-	-
Total	74368	73923	73720		106272	107678	107692

Overall, the pattern of land cover type change on Fort Benning is inconsistent with other data sources and land management directions (INRMP 2006, Prior et al 2007, Figure 92). The imagery data suggests that evergreen/hardwood area has increased since 2003, though this has been a primary focus for conversion to longleaf pine and mixed pine forest. Scrub/shrub has also increased during that period, while natural evergreen, planted evergreen and herbaceous land cover classes have declined. The decline in “natural evergreen” area may be due to conversion of offsite loblolly pine and mixed pine forest; however, when replanted one would expect an increase in herbaceous and planted evergreen coverage. Forest thinning of “natural pine” or “evergreen-hardwood” may result in spectral mis-interpretation as scrub/shrub immediately following the land management action. Some reduction in area of natural forest covers, through the establishment of the DMPRC, accounts for the increase in “bare ground.”

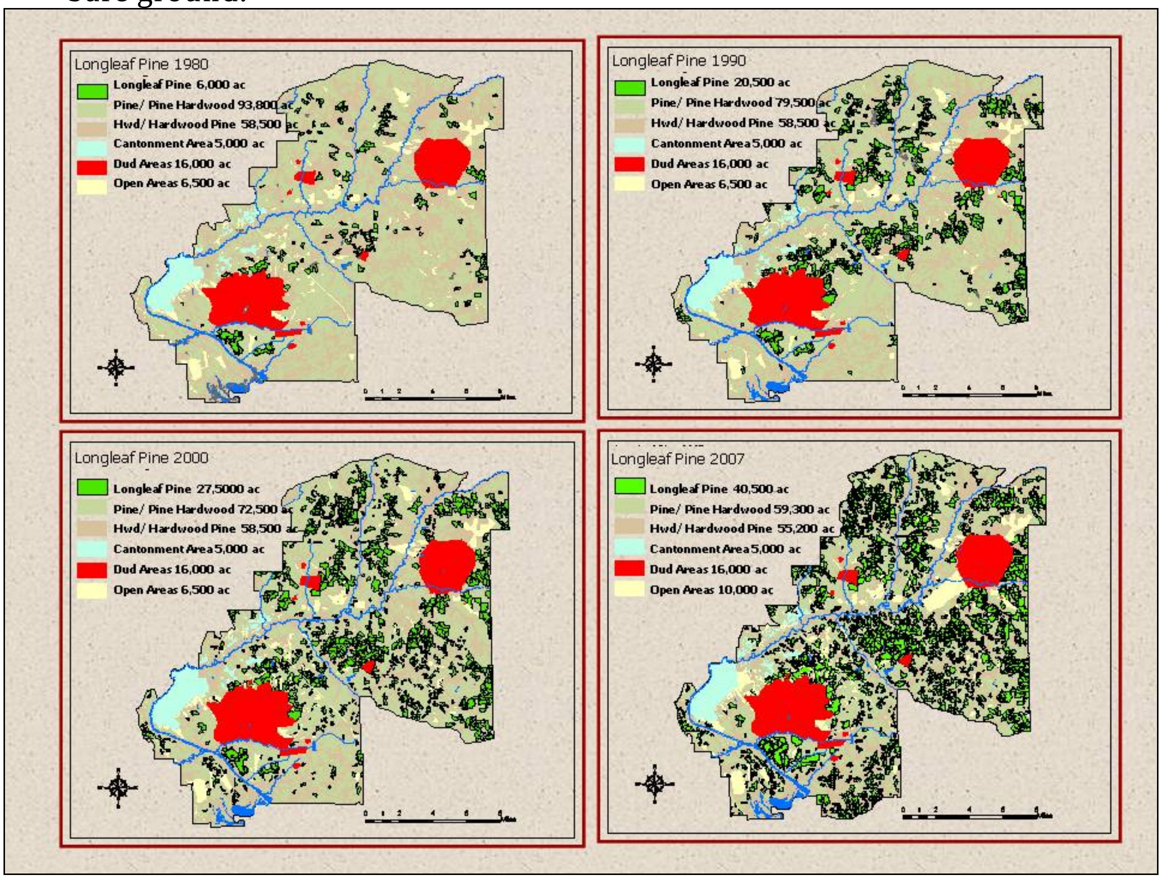

Figure 92. Land cover type change on Fort Benning (1980–2007).

Prior to full application, the following tasks should occur:

- Recommendations:

1. Improved “Ground truthing” using existing and additionally-collected canopy data may be needed to help redefine land cover types . These efforts should include defining the limits of compositional and structural ranges of each defined land cover type as well as improved definition of the habitat variability within.
2. Compare and analyze the algorithms used for classification. This includes comparison of different algorithms across different periods of coverage.

Conceivably the spectral signatures, and resulting algorithms, associated with some land cover types (e.g., upland pine forest) will continue to evolve with improving resolution and land management advancement toward the desired open pine forest-grassy under story settings. Therefore, algorithms based on locales at or near the desired condition should be developed.

3. Though resolution accuracy has increased overall; consistency with other data may have declined. This pattern is particularly evident for natural pine, planted pine, and pine-hardwood coverages, which are high-priority land management settings. Potentially, resolution accuracy may have increased for non-Fort Benning areas, but declined for certain sections of Fort Benning. Therefore, some consideration should be given to analyzing spatial patterns of residual or classification error. Further consideration that open forest settings and finer resolution is resulting in a most forest stands being spectral mosaics that are more strongly influenced by under story and forest floor spectral signatures.
4. Comparison and integration with other remote resources such as LIDAR, hyper spectral imagery, and aerial photography is also needed. These other remote data sources will likely replace original data sources such as enhanced thermatic mapper (ETM+); therefore, a crosswalk between remote resource types is needed to retain interpretive value of the original imagery.

- Application
  - Land cover classification is a critical resource for Fort Benning because it allows for remote assessment of conditions associated with difficult access. With the advancement of BRAC activities and further range usage, periodic access to remote areas to conduct field work will continue to be difficult; therefore, planning and environmental assessment will become more reliant on remote imagery and other GIS coverages. Further, multi-scale spatial assessments using field validated land cover classifications serves multiple purposes (watershed & water quality, forest growth & habitat quality, species suitability & connectivity, nutrient conservation & carbon budgets, etc.). Current and planned applications of land cover classifications include;
  - Watershed models to estimate water-use, water-retention, and interception differences between forest types within a watershed. Essentially each land cover type is assigned water-use and transfer criteria that are field based and connected to topography and

juxtaposition to streams. Spatially explicit watershed models can then be developed and correlated with hydrologic pattern of individual stream segments then cumulatively adjusted to various scales.

- Land cover classification is being used to assess C and nutrient dynamics. Each coverage type is assigned stocking values and functional process rates that are then partitioned across the landscape in proportion to occurrence. These values can then be cumulatively compared between watersheds or with the surrounding area.
- Assessments of habitat connectivity and fragmentation of RCW suitable habitat are made using forest and land coverage types. These same approaches can be used for other species of interest. Further work is needed in defining criteria associated with habitat assignment to land cover types as well as connectivity between existing and potential habitat units. Other remote data resources such as LIDAR and other hypers pectral coverages are more effective at delineating habitat and structure, these resources are not cost effective for assessing connectivity to off-post land conditions.
- Though hyper spectral coverages are more effective at detecting forest health problems, these data are more expensive and less likely to cover the entire area surrounding Fort Benning. Therefore, connectivity of spectral signatures between hyper spectal data and ETM+ data is needed to evaluate off-post conditions.
- Installation wide assessments of species richness patterns could be used to track the overall fitness of Fort Benning. Using species diversity equations recommended by the NRC report (2000); estimates of the impact of land conversion and land-use change could be made to estimate local & installation-wide change in species richness.

SERDP Ecosystem Characterization and monitoring initiative

White paper C4: A comparison of meteorological stations located at Fort Benning, GA and Columbus, GA Airport (A. Dale Magoun, Ph.D., Applied Research and Analysis, Inc.)

Purpose and scope

The purpose and scope of this data report is to describe the meteorological (MET) relationship of weather data as measured at the ten (10) strategically placed MET stations at Fort Benning, GA and the NCC controlled weather station located on the premises of the Columbus, GA airport. The MET of daily precipitation and temperatures are the two parameters under consideration and this report provides a historical depiction of these parameters and the interrelationships that exists.

Introduction

According to the Executive Summary of the Long-Term Monitoring Program Ecosystem Characterization and Monitoring Initiative (ECMI) Fort Benning, Georgia was selected as the first site for implementing the Strategic Environmental Research and Development Program Ecosystem Management Project (SEMP). Fort Benning occupies 73,813 hectares and is located in counties residing in both Georgia and Alabama and represents a transition between two ecological units – 1) the Coastal Plains and Flatwoods Sandy Hills Subsection and the Coastal Plains Upper Loam Hills Subsection. Fort Benning is traversed by several streams whose headwaters reside in the Southern Appalachian (Midland Plateau Central Uplands Subsection), which is immediately to the north of Fort Benning.

The ten (10) meteorological monitoring stations were distributed across the installation and were positioned to represent the complete complex at Fort Benning; however, they do not represent or correspond to any particular watershed. Each MET station was a permanent, self-contained, remotely accessed meteorological station and designed specially to collect information relative to air temperature, relative humidity, barometric pressure, solar radiation, wind speed, wind direction, precipitation and evaporation. Collection activities began on August 13, 1999.

The meteorological station located at the Columbus Metropolitan Airport (CSG) is located approximately 15 miles to the north of Fort Benning main complex. The weather station is operated by the National Climatic Data Center and has compiled a historical database of daily temperature extremes and precipitation totals. Historical records begin in January of 1948.

Background and historical information for Columbus, GA Air Port

As mentioned in the previous section, historical meteorological data recorded at the Columbus Metropolitan Airport exists and is maintained by the National Climatic Data Center. The historical record begins in 1948 and consists of daily temperature extremes (degrees F) and total precipitation amounts (inches). Table 35 below summarizes the historical data as recorded at this MET station (http://cirrus.dnr.state.sc.us/cgi-bin/sercc/cliMAIN.pl?ga2166)

Table 35. Columbus Metropolitan Airport MET Station historical summary.

Period of record: 7/ 1/1948 to 12/31/2005

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Average Max. Temperature (F)	57.7	61.5	68.7	77.0	84.0	89.6	91.5	90.9	86.0	77.3	67.7	59.3	75.9
Average Min. Temperature (F)	36.5	39.0	44.9	52.0	60.9	68.5	71.8	71.1	66.1	54.3	44.2	37.9	53.9
Average Total Precipitation (in.)	4.13	4.52	5.70	4.10	3.78	3.99	5.45	3.83	3.33	2.20	3.56	4.45	49.02
Average Total SnowFall (in.)	0.2	0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7
Average Snow Depth (in.)	0	0	0	0	0	0	0	0	0	0	0	0	0
Percent of possible observations for period of record. Max. Temp.: 100% Min. Temp.: 100% Precipitation: 100% Snowfall: 99.9% Snow Depth: 99.9%													

As is readily observed from Table 35, the annual average high temperature was 75.9 ° F; whereas, the annual average low temperature was 53.9 °F. The maximum average high temperature occurred in July (91.5 °F); whereas, the minimum average low temperature occurred in January (36.5 °F). Total annual rainfall for the period of record averaged 49.02 inches with the extremes occurring in March (5.70 inches) and October (2.20 inches). The average monthly rainfall is 4.085 inches. The NCDC data center also collects average snow depth. As can be seen from Table 35, snow depth over the period of record averaged 0.7 inches and occurred during the months of January through March; when the largest snow depth occurring in February.

Background and meteorological Information for Fort Benning, GA

The meteorological data recorded at Fort Benning, Georgia are maintained the U.S. Army Engineer Research and Development Center (USAERDC), Environmental Laboratory (EL) in Vicksburg, MS. Observations began in 1999 and contain meteorological data, collected on a fifteen (15) minute time scale, from the ten (10) strategically placed MET stations. The parameters measured are air temperature degrees C), relative humidity (percent RH), barometric pressure (millibars of Hg), solar radiation, wind speed (knots), wind direction (degrees from North), precipitation (mm) and evaporation. Table 36 displays the monthly average maximum and minimum air temperature and precipitation totals collectively for the ten MET stations. The average annual high temperature was 75.7 °F; whereas, the average annual low temperature was 53.3 °F. The maximum average high temperature occurred during July (91.0 °F) and the minimum average low temperature occurred during January (37.3 °F). Total annual rainfall averaged 41.88 inches. The maximum amount of monthly rainfall was 5.60 inches, which occurred in March; whereas, the minimum amount of rainfall was 1.75 inches, which occurred in October. The average monthly rainfall for this area and period of record was 3.49 inches.

Table 36. Fort Benning, GA MET Stations Historical Data Period of Record: 1/1/2000 – 2/1/2006.

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Average Max. Temperature (F)	59.7	62.6	70.5	77.1	84.5	88.2	91.0	90.1	85.1	77.7	69.4	58.3	75.7
Average Min. Temperature (F)	37.3	40.0	46.1	51.4	60.2	67.6	70.6	69.9	65.2	54.9	46.0	35.2	53.3
Average Total Precipitation (in.)	3.37	3.49	5.60	2.93	2.15	4.18	4.15	3.47	3.64	1.75	4.13	3.02	41.88

Table 37 displays the average number of days per month in which rainfall exceeded specific levels of 0.5 inches, 1.0 inches, 1.5 inches and 2.0 inches. Overall, the minimum number of days per month where rainfall exceeded 0.5 inches was averaged 1.69 days/month; whereas, the maximum number of days per month where rainfall exceeded 0.5 inches averaged 2.79 days and these occurred at MET stations 4 and 6, respectively. Historically, the number of days per month where rainfall exceeded 0.5 inches at the Columbus Airport MET station averaged 2.75 days/month. Table 37 also shows that the average number of days/per month where precipitation totals exceeded 1 inch ranged from a low of 0.69 days/month to 1.19 days per month; whereas, the average at Columbus airport was 1.17 days. Table 37 continues to display average days/month for rainfall totals exceeding 1.5 and 2.0 inches; however, the database at Columbus Airport did not reveal this particular information.

Table 37. Monthly average number of rain days, Fort Benning and Columbus Airport.

		Average Number per Month			
		Rain Totals Exceeding			
	SITE	0.5 inches	1.0 inches	1.5 inches	2.0 inches
Meteorological Sampling Station	1	2.35	0.91	0.48	0.20
	2	2.36	1.03	0.46	0.17
	3	2.36	1.00	0.53	0.29
	4	1.69	0.69	0.33	0.15

	5	2.40	0.97	0.49	0.25
	6	2.79	1.19	0.74	0.30
	7	2.07	0.84	0.39	0.16
	8	2.45	1.07	0.45	0.14
	9	1.88	0.75	0.39	0.17
	10	2.45	0.97	0.33	0.15
	Columbus, GA Airport	2.75	1.17	NA	NA

Table 38 below summarizes the meteorological statistics fixing the period of record for both sites during the time span of January 2000 through February 2006 for the Fort Benning and Columbus Airport MET stations, respectively. Whereas, during this same time interval, the low temperatures averaged 37.3 °F and 37.6 °F and the high temperatures averaged 91.0 °F and 92.4 °F, respectively for Fort Benning and Columbus Airport. Precipitation totals averaged 46.4 inches at Fort Benning; whereas, the average as reported by the NCDC data set for the same sampling period was 41.9 inches at the Columbus Metropolitan Airport. Monthly averages were 3.87 inches and 3.49 inches, respectively for Fort Benning and Columbus Metropolitan Airport.

Correlation analysis

The major task for this research was to investigate the relationship between the meteorological records as recorded at the ten (10) Fort Benning MET stations and the NCDC site at the Columbus Metropolitan Airport. As such, records from each of the two data sets were merged by date so that concomitant meteorological information could be related.

Minimum Daily Temperature. The correlation coefficient between the minimum daily temperatures that were observed and recorded at the two sites was 0.9701 and is shown in Table 39 below and depicted in Figure 93. The linear relationship as seen in Figure 93 explains 94.11 percent of the total variance. Thus, the temperature recordings at the Columbus Airport site appear to be a good predictor to the temperature recordings at the Fort Benning MET sites.

Table 38. Meteorological data period of record: 1/2000 through 2/2006 monthly averages,

	Fort Benning, GA			Columbus, GA Airport		
	Period of Record: 1/2000 – 2/2006			Period of Record: 1/2000-2/2006		
Month	Average Total Precipitation (inches)	Average Minimum Temperature (F)	Average Maximum Temperature (F)	Average Total Precipitation (inches)	Average Minimum Temperature (F)	Average Maximum Temperature (F)
Jan	2.83	37.6	58.6	3.37	37.3	59.7
Feb	3.73	40.9	62.2	3.49	40.0	62.5
Mar	6.21	47.2	70.0	5.61	46.0	70.4
Apr	3.56	54.0	77.4	2.93	51.4	77.1
May	3.01	62.8	84.6	2.15	60.2	84.5
June	4.87	69.8	89.1	4.18	67.6	88.2
July	5.17	73.2	92.4	4.15	70.6	91.0
Aug	3.84	72.8	91.2	3.47	69.9	90.1
Sep	4.02	67.4	85.6	3.64	65.2	85.1
Oct	1.97	56.5	77.7	1.75	54.9	77.7
Nov	4.19	47.4	69.4	4.13	46.0	69.4
Dec	2.98	37.5	58.7	3.02	35.2	58.3
Annual	46.4	55.6	76.4	41.9	55.6	76.5

Table 39. Correlation – minimum air temperature.

	Columbus	Fort Benning
Columbus	1.0000	0.9701
Fort Benning	0.9701	1.0000
Note: 53 rows not used due to missing or excluded values or frequency or weight variables missing, negative or less than one.		

As with the minimum temperature, the correlation between the maximum temperatures was 0.9835 and is given in Table 40 below. Figure 94 displays the linear relationship between these two meteorological parameters and further substantiates the association between the minimum air temperature recorded at Columbus Metropolitan Airport and recordings observed at the MET stations located on the Fort Benning installation.

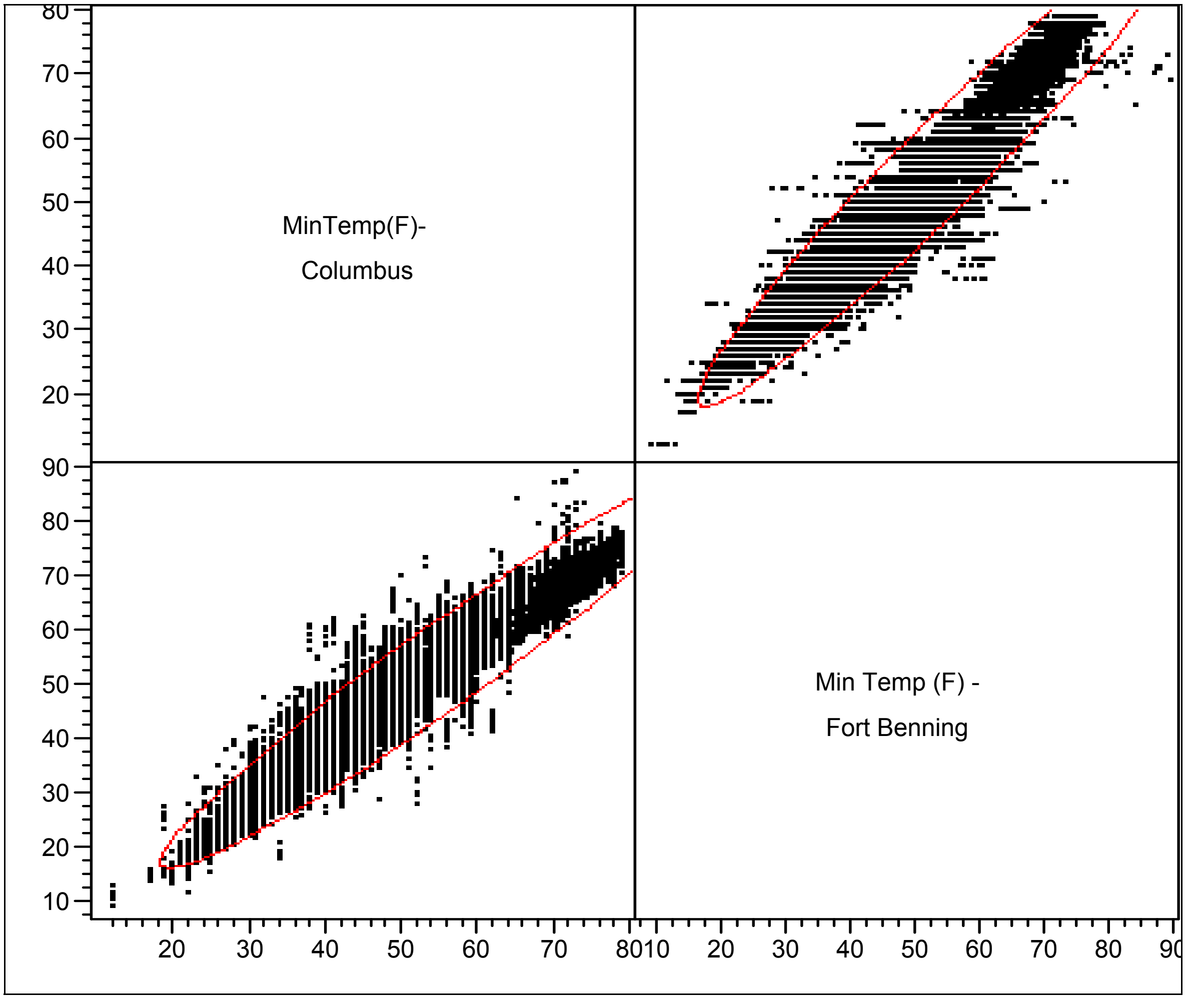

Figure 93. Minimum Temperature Scatter Plots.

Table 40 below displays the correlation coefficient as measured on the meteorological parameter of Maximum Air Temperature for the two locations. The correlation of 0.9835 indicates a strong relationship between the measurements recorded at Columbus Airport and Fort Benning and that the linear model would explain 96.7% of the total variation. Figure 94 further substantiates the linear relationship.

Table 40. Correlation – Maximum Air Temperature

	Columbus	Fort Benning
Columbus	1.0000	0.9835
Fort Benning	0.9835	1.0000
Note: 61 rows not used due to missing or excluded values or frequency or weight variables missing, negative or less than one.		

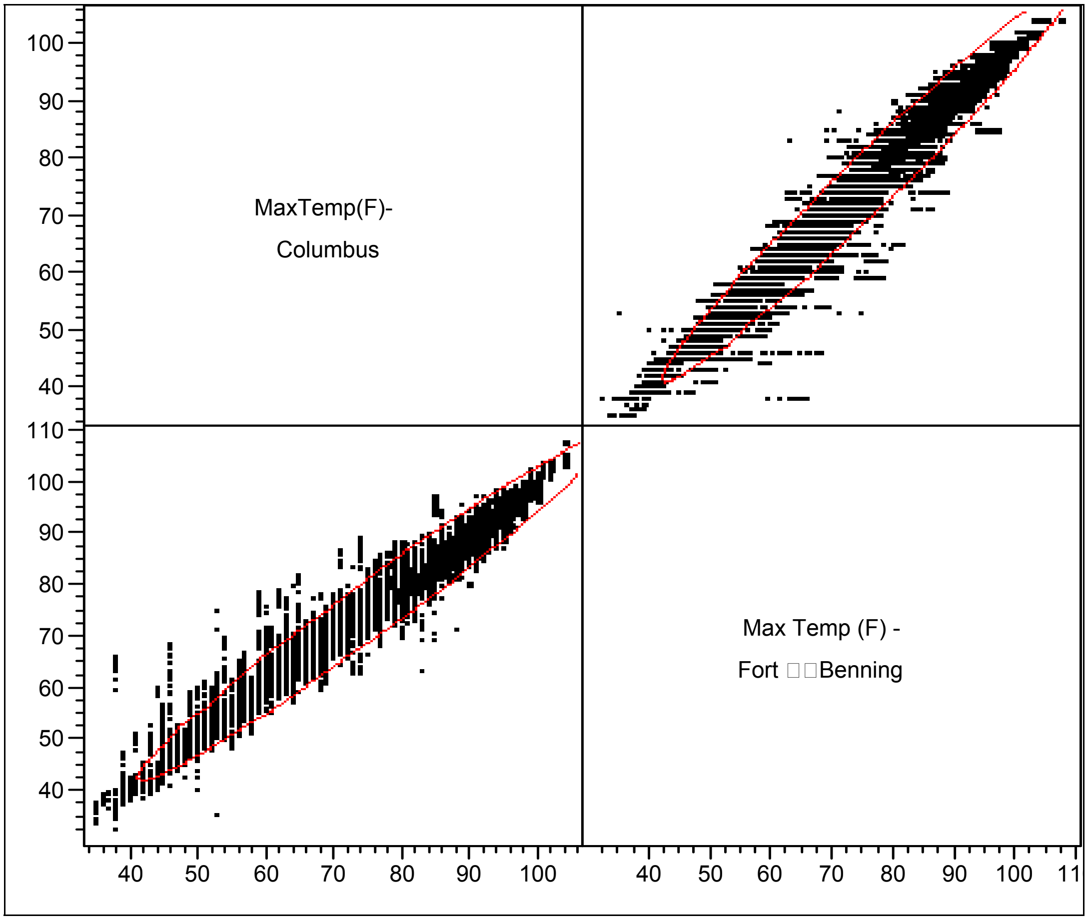

Figure 94. Maximum temperature scatterplot plot matrix.

Individually, each of the ten MET stations at Fort Benning was also highly correlated with the readings observed at the Columbus Airport. Table 41 displays the individual MET station correlations for both the Minimum and Maximum Air Temperatures. The correlations for Minimum Temperature ranged from a low of 0.9613 to a high of 0.9758; whereas, for the Maximum Temperatures the correlations ranged from a low of 0.9816 to a high of 0.9865. These individual MET site correlations provide additional evidence of the linearity between temperature readings at the Columbus Metropolitan Airport and the meteorological observation sites on the Fort Benning installation.

Table 41. Correlation Coefficients by Fort Benning MET Site Min/Max Air Temperature

Fort Benning MET Site	Minimum Temperature	Maximum Temperature
1	0.9758	0.9814
2	0.9698	0.9858
3	0.9613	0.9845

Fort Benning MET Site	Minimum Temperature	Maximum Temperature
4	0.9766	0.9841
5	0.9643	0.9841
6	0.9790	0.9865
7	0.9783	0.9850
8	0.9768	0.9862
9	0.9711	0.9853
10	0.9658	0.9816

Precipitation

The correlation between the amounts of daily precipitation observed at both sites was 0.6714. A linear model thus explains only 45.1 percent of the total variation (R-Square) observed. An R-Square of this low magnitude indicates that a linear model may not adequately explain the relationship between the amount of precipitation observed at Columbus Airport and the amount observed collectively at the ten Fort Benning MET stations. The scatter plots given in Figure 95 also substantiate the variability of daily precipitation. The large variation is probably due to the summertime scatter showers and not so much on the lack of correlation. When considering the individual correlations, Table 42 lists that the maximum correlation between daily amounts of precipitation was 0.7324 and the minimum correlation was 0.6114. These occurred, respectively, at MET stations 1 and 10. Although, the scatter plots tend to show large variation, the correlation coefficients do indicate that the relationship does exist; however, it may also depend on other factors that are available in these data sets. Factors such as relative humidity and solar radiation may also play a part in predicting daily amounts of precipitation at Fort Benning from the amount recorded at the Columbus Airport. It may also indicate that a predictive daily precipitation model may not be adequate in determining the relationship and that one might consider weekly amounts of precipitation rather than daily.

Table 42. Correlation – Daily Precipitation

	Columbus	Fort Benning
Columbus	1.0000	0.6714
Fort Benning	0.6714	1.0000
Note: 1905 rows not used due to missing or excluded values or frequency or weight variables missing, negative or less than one.		

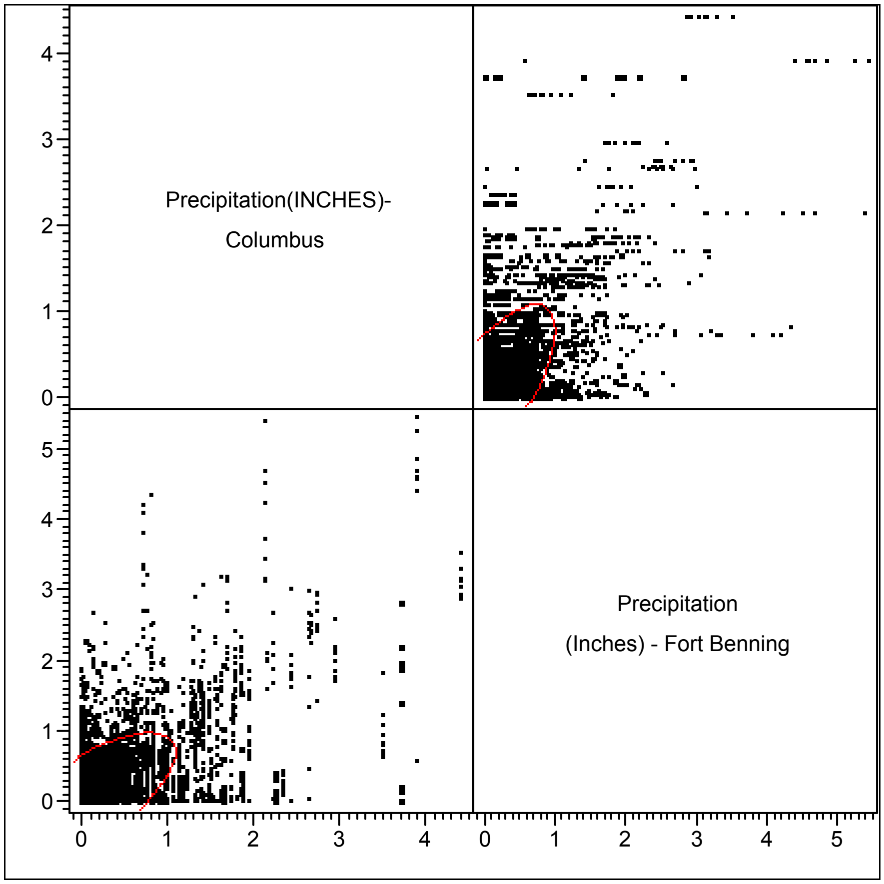

Figure 95. Daily Precipitation Scatterplot Plot Matrix

Table 43. Correlation Coefficients by Fort Benning MET Site Total Precipitation

Fort Benning MET Site	Correlation Coefficient
1	0.7324
2	0.6766
3	0.6816
4	0.6243
5	0.6582
6	0.6838
7	0.6815
8	0.7215
9	0.6427
10	0.6114

Summary and conclusions

The correlation analysis indicates that the meteorological readings observed at the Columbus Metropolitan Airport could be used to predict with good accuracy the meteorological parameters of minimum air temperature and maximum air temperatures. The correlation coefficients between the sites of Columbus Airport and the U.S. Army installation at Fort Benning were 0.9701 and 0.9835, respectively, for the air temperature parameters. As for as the meteorological parameter of daily precipitation, the correlation coefficient between to the two sites was 0.6724. Although this coefficient was not as strong as the association with the air temperature parameters, it is sufficiently differ from zero and does indicate that daily precipitation at Columbus Airport may be used as a predictor of daily precipitation at Fort Benning. The linear models which best describes these relations are given below in Table 44 and the Appendices which follows.

Table 44. Linear Predictors

Parameter	R-Square	Linear Model
Minimum Air Temperature (degrees F)	94.1%	$MinAT_{FB} = -0.388 + 0.9747\ MinAT_{CMAP}$
Maximum Air Temperature (Degrees F)	96.7%	$MaxAT_{FB} = 3.798 + 0.9497\ MaxAT_{CMAP}$
Daily Precipitation (inches)	45.1%	$DailyP_{FB} = 0.0303 + 0.6260\ DailyP_{CMAP}$

Note: $MinAT_{FB}$: Minimum Air Temperature at Fort Benning
$MinAT_{CMAP}$: Minimum Air Temperature at Columbus Metropolitan Airport
$MaxAT_{FB}$: Maximum Air Temperature at Fort Benning
$MaxAT_{CMAP}$: Maximum Air Temperature at Columbus Metropolitan Airport
$DailyP_{FB}$: Daily Precipitation at Fort Benning
$DailyP_{CMAP}$: Daily Precipitation at Columbus Metropolitan Airport

As can be readily seen from Table 44, the Daily precipitation model does not have good predictor characteristics as it only explains 45.1 percent of the total variation observed at the Fort Benning installation. This is most probably due to the isolated showers that are very prominent between late spring and early fall. Albeit, the relationship is not strong, it is present and one might consider using the precipitation characteristics at the local airport as a predictor of the precipitation characteristics observed at Fort Benning.

13 Linear Models

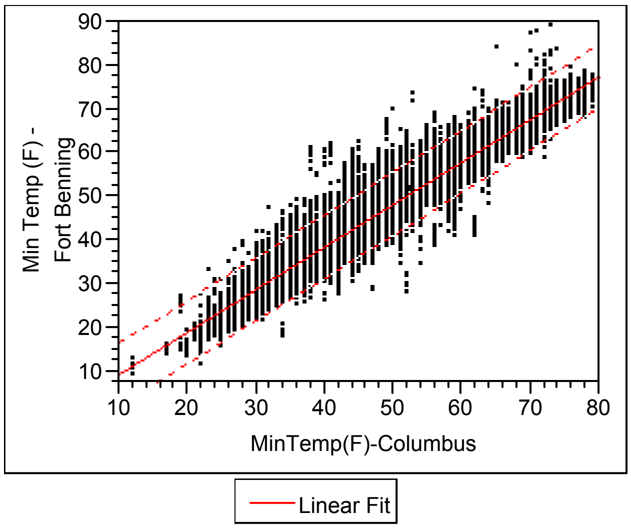

Figure 96. Bivariate Fit of Min Temp (F) - Fort Benning By MinTemp(Degrees F)-Columbus

Linear Fit:

Min Temp (F) - Fort Benning = -0.387977 + 0.9747375 MinTemp(F)-Columbus

Table 45. Summary of Fit

R-Square	0.94116
R-Square Adjusted	0.94116
Root Mean Square Error	3.68158
Mean of Response	53.25075
Observations (or Sum Wgts)	18795

Table 46. Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	4074295.6	4074296	300596.0
Error	18793	254721.4	14	Prob > F
C. Total	18794	4329017.0		0.0000

Table 47. Parameter Estimates

Term		Estimate	Std Error	t Ratio	Prob>|t|
Intercept		-0.387977	0.101452	-3.82	0.0001
MinTemp(F)-Columbus		0.974736	0.001778	548.27	0.0000

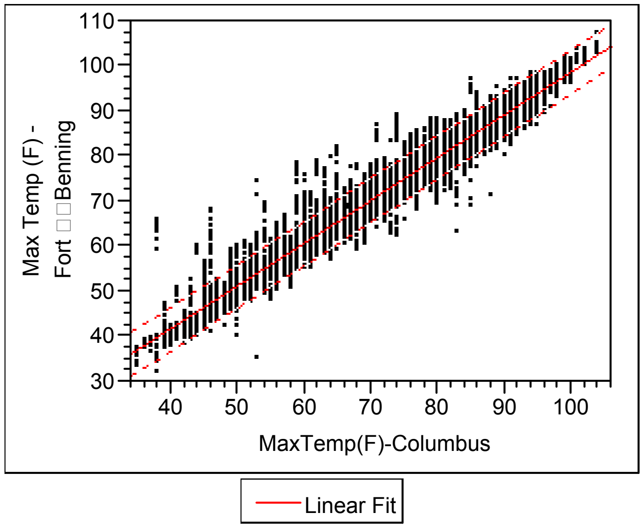

Figure 97. Bivariate Fit of Maximum Air Temperature (°F), Fort Benning By MaxTemp(°F)-Columbus.

Linear fit:

Max Temp (F) - Fort Benning = 3.7978534 + 0.9497163 MaxTemp(F)-Columbus

Table 48. Summary of fit.

R-Square	0.96731
R-Square Adjusted	0.96731
Root Mean Square Error	2.47823
Mean of Response	75.75306
Observations (or Sum Wgts)	18787

Table 49. Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	3413704.6	3413705	555827.3
Error	18785	115371.2	6.141664	Prob > F
C. Total	18786	3529075.8		0.0000

Table 50. Parameter Estimates

Term		Estimate	Std Error	t Ratio	Prob>|t|
Intercept		3.7978534	0.098193	38.68	<.0001
MaxTemp(F)-Columbus		0.9497163	0.001274	745.54	0.0000

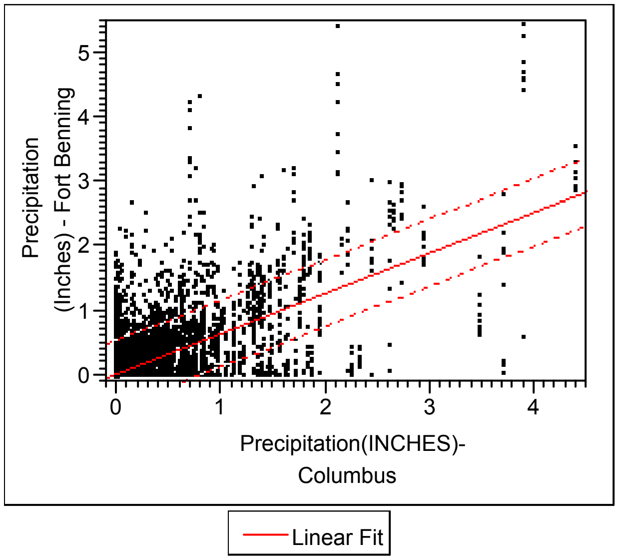

Figure 98. Bivariate Fit of Precipitation (Inches) - Fort Benning By Precipitation(INCHES)-Columbus.

Linear fit:

Precipitation (Inches) - Fort Benning = 0.0302676 + 0.6260064 Precipitation (Inches)-Columbus

Table 51. Summary of fit.

R-Square	0.450785
R-Square Adjusted	0.450753
Root Mean Square Error	0.265018
Mean of Response	0.119643
Observations (or Sum Wgts)	16943

Table 52. Analysis of variance.

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	976.6004	976.600	13904.86
Error	16941	1189.8423	0.070	Prob > F
C. Total	16942	2166.4427		0.0000

Table 53. Parameter estimates.

Term		Estimate	Std Error	t Ratio	Prob>|t|
Intercept		0.0302676	0.002173	13.93	<.0001
Precipitation(INCHES)-Columbus		0.6260064	0.005309	117.92	0.0000

SERDP ecosystem characterization and monitoring initiative

White paper C5: Meteorological study, Fort Benning, GA and surrounding climate regions (A. Dale Magoun, Ph.D., Applied Research and Analysis, Inc.)

Introduction.

Meteorological studies usually involve a detailed look at the typical parameters of precipitation, maximum and minimum temperatures, relative humidity, solar radiation and wind speed and direction, and the investigation can focus on a daily changes, a monthly trends, or trends over any long-term period of interest. Time intervals other than daily are usually expressed as averages or totals depending on the parameter under consideration. For example, temperatures on a monthly basis may reflect average maximum temperatures or the average minimum temperatures. Additionally, one could consider the average of the average daily temperatures and total precipitation for a period of interest. Although the use of these meteorological statistics is common practice, other indices, such as the Palmer Drought Index (PDI) or the Standardized Precipitation Index (SPI) could also be used to assist with the characterization of a region from a historical perspective. This study uses the SDI precipitation index in order to investigate the interdependent structure of the climate regions surrounding Fort Benning, Georgia.

Precipitation indices

The PDI and SPI characterizes the drought index based upon a given time period and can be readily displayed using GIS software. The visual image can quickly depict drought conditions for any given area. Wayne Palmer developed the PDI instrument in the 1960's and the methodology focuses on the use of temperature and rainfall information in a formula to determine dryness. The PDI has become the semi-official drought index and it is most effective in determining long-term drought. It uses a 0 as normal, and drought is shown in terms of minus numbers. For example, minus 2 is moderate drought, minus 3 is severe drought, and minus 4 is extreme drought. The Palmer Index can also reflect excess rain using a corresponding level reflected by plus figures; i.e., 0 is normal, plus 2 is moderate rainfall, etc. The advantage of the Palmer Index is that it is standardized to local climate, so it can be applied to any part of the country to demonstrate relative drought or rainfall conditions (1).

The Standardized Precipitation Index (SPI) was introduced by McKee etal (2) and represents another method for measuring drought that is different from the Palmer drought index (PDI). Like the PDI, this index is negative for drought and positive for wet conditions. The PDI algorithm is a water balance index that consider water supply (precipitation), demand (evapotranspiration) and loss (runoff); the Standardized Precipitation Index (SPI) is based on the probability of recording a given amount of precipitation. The probabilities are standardized so that an index of zero indicates the median or normal precipitation amount; whereas, a negative index value reflects drought conditions, and a positive index value represents wet conditions. As the dry or wet conditions become more severe, the index becomes more negative or positive. The SPI is typically computed on a time scale ranging from one month to 24 months so that the various scales of both short-term and long-term drought can be considered (3). More information on the methodology behind SPI can be found in Chapter 3 of Daniel Edwards' thesis (4), which is reprinted in Appendix I of this report. This document details the mathematics used in SPI calculation. Executable images of the programs to calculate these indices can be found at the National Agricultural Decision Support System (NADSS) home page http://nadss.unl.edu/index.jsp. One can follow the links from that page to the pages containing information about the PDI and SPI. Once there, downloads can be performed.

Meteorological summaries

There are ten (10) meteorological weather stations at Fort Benning; however, the history only contains precipitation data dating back to 1999. Most researchers in the field indicate that at least twenty-five (25) if not more years of data need to be collected in order to understand the drought/wet conditions at a given site. To complement the study, a detailed history dating back to 1895 from five surrounding national weather service (NWS) climate regions was obtained along with a historical perspective from the Columbus Metropolitan airport which dated to 1948. The climate region designations from Alabama were climate regions 05, 06 and 07, whereas; in Georgia the climate regions were 04 and 07. Figure 99 below displays the geographical image describing the area.

Geographically Alabama climate region 05 represents the Piedmont Plateau Division, region 06 represents the Prairie Division, and 07 represents the Coastal Plain Division. In Georgia, Climate Region 04 represents the West Central Division, whereas; 07 represens the Southwest Division. Columbus Metropolitan airport is located in the West Central Division. The historical average precipitation amounts (in inches) for these climate regions and the study sites of Fort Benning and Columbus Metropolitan Airport are given in Table 54.

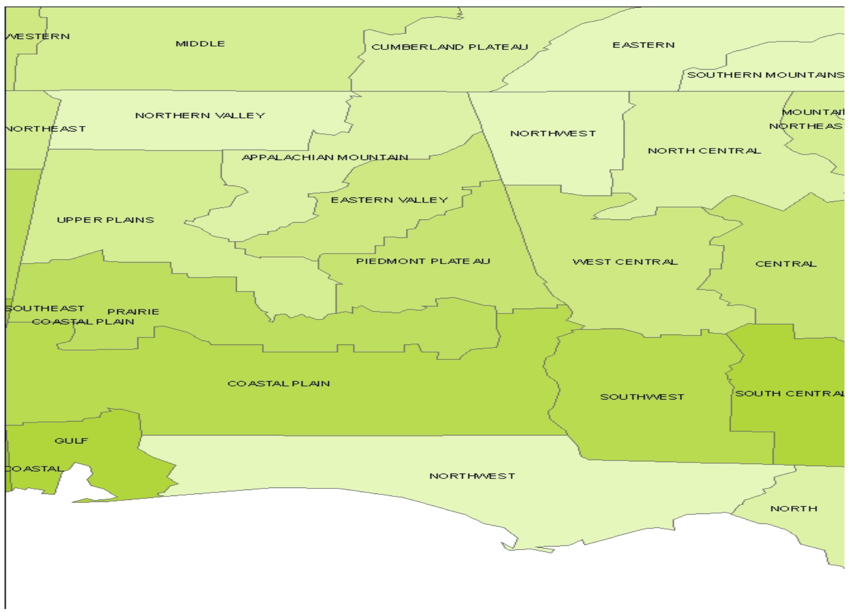

Figure 99. Regional map.

Table 54. Historical monthly precipitation averages (inches), 1895 – 2007.

Month	Fort Benning	Columbus AP	Alabama Climate Regions 1895 - 2007			Georgia Climate Regions 1895 - 2007	
	1999-2006	1948-2007	CR 05	CR 06	CR 07	CR 04	CR 07
1	3.36	4.12	4.87	4.52	4.76	4.46	4. 56
2	3.40	4.48	5.25	4.95	5.08	4.90	4.69
3	5.32	5.64	6.09	5.72	5.75	5.67	5.33
4	2.76	4.09	4.75	4.54	4.46	4.20	3.86
5	2.31	3.72	3.70	3.62	4.04	3.59	3.53
6	3.87	4.00	4.15	3.94	4.66	4.13	4.79
7	3.97	5.40	5.22	4.94	6.06	5.36	6.22
8	3.06	3.83	3.85	3.47	4.49	4.02	4.75
9	3.37	3.33	3.81	3.56	4.35	3.41	4.05
10	1.95	2.21	2.78	2.71	2.68	2.63	2.29
11	3.90	3.58	3.71	3.39	3.58	3.22	2.98
12	2.94	4.30	4.95	4.88	5.00	4.50	4.18

Summaries

The sections below summarize the data from a historical perspective as well as a recent perspective. Correlation analysis is the primary basis of the summaries as well as descriptive statistics that describe the relationships between various meteorological parameters of interest.

Historical summaries.

As is evident from Table 54, historically rainfall amounts ranged from a minimum of 2.29 inches in GA-CR 07 during October to a maximum of 6.22 inches, which also occurred in GA-CR 07 during the month of July. Historically, the average monthly precipitation was 4.33 inches with a standard deviation of 0.91 inches. At Fort Benning, the precipitation totals ranged from a minimum of 1.95 inches for October to a maximum of 5.32 inches in March with an average precipitation of 3.34 inches with a standard deviation of 0.88. Historically, the Columbus Metropolitan airport station reported a minimum average monthly precipitation of 2.21 in October and a maximum average of 5.64 in March. The average precipitation reported at Columbus AP was 4.06 inches with a standard deviation of 0.90 inches.

One can readily see from Table 54 that the sampling window at Fort Benning truly represents a short period where precipitation amounts are much less than the historical averages observed at the NCDC Climate Region Divisions and at the Columbus Metropolitan airport. Drought indices researcher recognize the deficiencies of short term meteorological windows and hence, recommend at least a history database of at least twenty-five years in order to characterize the drought/non-drought conditions of an area.

Table 55 describes the temperature regimes for the area. Temperatures ranged from low average of 44.7 degrees F to a high of 80.94 and these average extremes occurred during the months of January and July, respectively. Overall, the yearly averaged temperature was 63.44 degrees F with a standard deviation of 12.86 degrees. Fort Benning stations reported average monthly temperatures ranging between a low of 47.70 degrees F to 81.07 degrees F with an average of 65.08 and a standard deviation of 12.37. Columbus AP reported temperature averages ranging from 47.13 to 81.69 degrees F with an average of 64.96 degrees F and a standard deviation of 13.00 degrees. Table 56 displays the monthly average temperatures for the area and exhibits the consistency in the surface temperature ranges as would be expected.

Table 55. Historical monthly temperature averages (°F).

Month	Fort Benning	Columbus AP	Alabama Climate Regions 1895 - 2007			Georgia Climate Regions 1895 - 2007	
	1999-2006	1948-2007	CR 05	CR 06	CR 07	CR 04	CR 07
1	48.51	47.13	44.90	46.96	48.55	44.70	49.55
2	51.27	50.22	47.15	49.55	50.94	47.08	51.91
3	58.22	56.86	54.52	56.68	57.92	54.39	58.65
4	64.90	64.52	61.80	63.97	64.83	62.12	65.51
5	72.14	72.49	69.80	71.91	72.42	70.15	73.24
6	78.00	79.03	76.79	78.72	78.63	76.92	79.22
7	81.07	81.68	79.19	80.94	80.46	79.22	80.92
8	80.54	81.05	78.53	80.46	80.12	78.64	80.54
9	75.02	76.03	73.96	75.86	75.91	73.71	76.70
10	66.09	65.78	63.27	65.24	65.93	63.21	67.02
11	57.50	55.95	53.17	55.03	56.12	53.20	57.27
12	47.70	48.82	46.07	48.00	49.55	45.93	50.30

Monthly precipitation summaries.

Table 56 exhibits the average monthly precipitation amounts by location for the time period of August 1999 – December 2006. This time span covers the sampling window of the SEMP program at Fort Benning. During this window, the maximum monthly precipitation was 6.47 inches and was observed during the month of June in Alabama Climate Region 07. The minimum monthly average of 1.95 inches was observed at Fort Benning, GA during the month of October. Statistically, the Location by Site average precipitation amounts shown in Table 56 were significant ($F = 26.04$, p-value < 0.0001 for Monthly averages and $F = 10.96$, p-value < 0.0001 for Location averages). The Tukey-Kramer mean separation test indicated that the largest amounts of precipitation occurred during the months of March, June and July and the least amount occurred during October. With regards to location, the orthogonal contrast indicated that the average rainfall amounts in the three referenced Alabama Climate Regions recorded significantly more rainfall than the tow Georgia Climate Regions ($t = 3.34$, p-value = 0.00014) by an average of 0.4247 inches. The Columbus

Table 56. Average monthly precipitation, 1999 – 2006.

Month	Averages	Fort Benning	Columbus AP	Alabama Climate Regions			Georgia Climate Regions	
				CR 05	CR 06	CR-07	CR-04	CR 07
1	3.51	3.36	2.83	4.27	3.86	3.54	3.65	3.07
2	4.05	3.40	3.73	4.48	4.90	4.19	4.04	3.60
3	5.73	5.32	6.21	6.18	5.49	5.44	5.77	5.74
4	3.84	2.76	3.56	4.57	4.50	4.24	3.61	3.65
5	3.38	2.31	3.01	4.56	3.91	3.54	3.62	2.66
6	5.18	3.87	4.87	4.74	4.69	6.47	5.30	6.28
7	5.39	3.97	5.17	6.11	4.91	6.06	5.42	6.09
8	4.04	3.06	3.59	3.86	4.29	5.25	3.61	4.63
9	4.13	3.37	3.67	4.06	3.98	4.80	4.02	5.02
10	2.45	1.95	2.04	2.42	2.81	3.38	2.45	2.11
11	4.33	3.90	3.83	5.09	4.88	5.06	4.14	3.43
12	3.55	2.94	2.83	3.98	4.12	4.41	3.18	3.41
Averages	4.13	3.35	3.78	4.53	4.36	4.70	4.07	4.14

Metropolitan airport meteorological station recorded average was not significantly different from that recorded in the two Georgia Climate Regions ($t = 1.918$, p-value=0.0594). Fort Benning, however, did show significantly smaller amounts of recorded precipitation averages that both the two Columbus Climate Regions ($t = 4.429$, p-value<0.0001) and the Columbus Metropolitan airport ($t = 2.17$, p-value = 0.0333). The Columbus Metropolitan airport annual average precipitation exceeded that observed at Fort Benning by 0.4278 inches.

Correlation analysis

Although the monthly average precipitation amounts vary significantly between locations, the relationship between these amounts are sufficiently high as indicated in Table 57 . The correlation between the monthly precipitation amounts observed at Fort Benning exhibits a significant relationship with all areas. The correlation between the amount of precipitation observed at Fort Benning and the Columbus Metropolitan airport was 0.9126. Whereas with the NOAA climate regions the correlations were 0.8117, 0.7948, 0.8153, 0.8909, and 0.8446, respectively for climate regions 05, 06 and 07 in Alabama and 04 and 07 in Georgia. Correlations at these levels provide evidence that relationship can be established and used at these various locations to help predict precipitation events at Fort Benning, GA on a monthly basis. The model which best describes this relationship is

$$FB = 0.0685401 + 0.480338 * CGAP + 0.1832998 * ACR06 + 0.1625941 * GCR07$$

Where:

FB: predicted monthly precipitation at Fort Benning
CGAP: monthly precipitation at Columbus Metropolitan airport
ACR06: monthly precipitation in Alabama's climate region 06
GCR07: monthly precipitation in Georgia's climate region 07

The model described above explained 86.47% of the total variability of the Fort Benning monthly precipitation totals and exhibited no indications of any lack of fit.

Table 57. Multivariate Correlations, 1999 –2006.

		Columbus Airport	Fort Benning	Alabama Climate Regions			Georgia Climate Regions	
				CR-05	CR-06	CR-07	CR-04	CR-07
Columbus Airport		1.0000	0.9126	0.8142	0.7734	0.8060	0.9260	0.8521
Fort Benning		0.9126	1.0000	0.8117	0.7948	0.8153	0.8909	0.8446
Alabma	CR-05	0.8142	0.8117	1.0000	0.8671	0.8014	0.8996	0.7352
	CR-06	0.7734	0.7948	0.8671	1.0000	0.8709	0.8128	0.7157
	CR-07	0.8060	0.8153	0.8014	0.8709	1.0000	0.8294	0.8494
Georgia	CR-04	0.9260	0.8909	0.8996	0.8128	0.8294	1.0000	0.8473
	CR-07	0.8521	0.8446	0.7352	0.7157	0.8494	0.8473	1.0000

Annual precipitation.

Another measure of interest to this study was to the total annual precipitation at Fort Benning. Annual precipitation serves as part of watershed models and assists in the prediction of erosion effects. Table 58 below shows the estimated annual precipitation totals by meteorological site at Fort Benning and the surrounding climate regions. Annual precipitation was estimated from January 2000 through December 2006. Observations at Fort Benning recorded in 1999 were not consistently recorded at all sites and all months, thus, the 1999 data was eliminated from this computation.

As can be seen from Table 58, average annual precipitation observed at Fort Benning ranged from a minimum of 32.50 inches (825.50 MM) to a maximum of 47.58 inches (1208.53 MM). These values were observed at meteorological stations 9 and 6, respectively. Correspondingly, the regional data measured by the NOAA indicated that the Columbus Airport readings averaged 46.39 inches (1178.31MM) for the same sampling window. Likewise, the Alabama regions reported 55.13 inches (1400.30 MM), 53.16 inches (1350.26 MM), and 57.47 inches (1459.74 MM), respectively for climate regions 05, 06, and 07. The Georgia regions reported annual averages of 49.34 inches (1253.24 MM) and 50.66 inches (1286.76 MM). From this table, it appears that the annual readings observed at Fort Benning are consistently lower than those observed at the surrounding sites.

Table 58. Annual precipitation, 2000 – 2006.

Site/Climate Region	Site	Average Annual Precipitation (Inches)	Average Annual Precipitation (MM)
Fort Benning	1	42.50	1079.50
	2	41.02	1041.91
	3	39.57	999.83
	4	33.57	852.68
	5	41.74	1060.26
	6	47.58	1208.53
	7	37.59	954.79
	8	41.98	1066.29
	9	32.50	825.50
	10	36.71	932.43
Columbus Airport		46.39	1178.31
Alabama Climate Regions	05	55.13	1400.30
	06	53.16	1350.26
	07	57.47	1459.74
Georgia Climate Regions	04	49.34	1253.24
	07	50.66	1286.76

Probability distribution modeling.

Thom (1966) found the gamma distribution to fit climatological precipitation time series well. The gamma distribution is defined by its frequency or probability density function and is best described in Chapter 3 of Dan Edward's master thesis (http://ccc.atmos.colostate.edu/pub/spi.pdf). The gamma distribution is best described by its shape and scale parameters and is a skewed distribution and is represented by the following mathematical form:

$$f(x;k,\theta) = x^{k-1}\frac{e^{-x/\theta}}{\theta^k\,\Gamma(k)} \text{ for } x > 0 \text{ and } k,\theta > 0.$$

where k and θ represent the shape and scale parameters, respectively.

The gamma distribution represents a skewed distribution. Families of the gamma are given in Figure 100 below for different values of k and θ. The descriptive statistics along with the histograms of the monthly precipitation data at Fort Benning are given in Appendix I. In addition, the gamma distribution is fitted for the monthly precipitation totals recorded at each meteorological sampling station. Point and interval estimates for the shape and scale parameters of the gamma distributions are given in Table 59.

k-shape, θ-scale

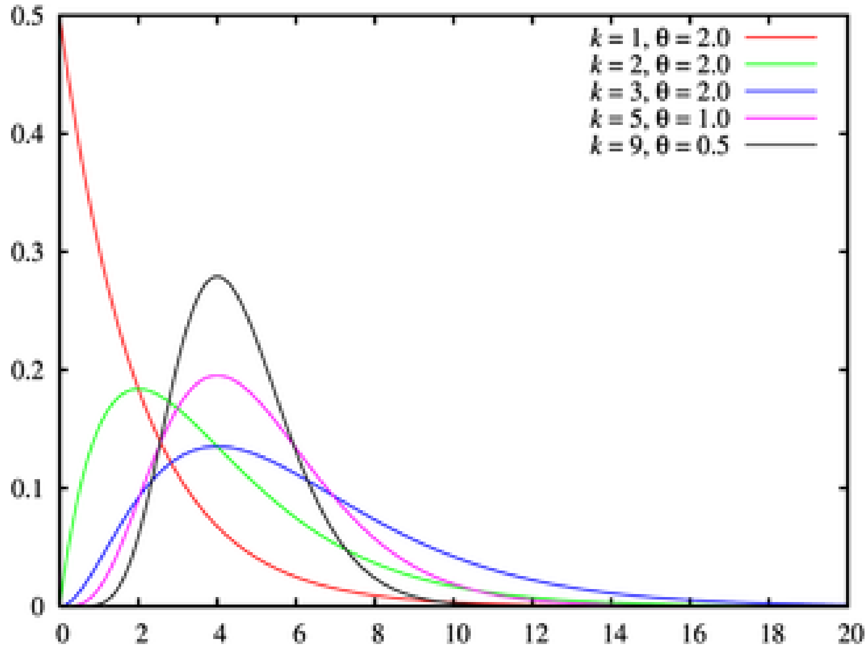

Figure 100. Gamma distributions.

The gamma distribution is used to estimate the probability recording a precipitation amount of at most x-inches. The cumulative gamma distribution is given by

$$F(x;k,\theta) = \int_0^x f(u;k,\theta)\,du = \frac{\gamma(k, x/\theta)}{\Gamma(k)}$$

The cumulative probability is then used to extrapolate to the standard normal distribution so that the Standardized Precipitation Index value is obtained. Since the gamma distribution is only defined for non-zero positive values, then the cumulative probabilities must be weighted according to the empirical probability of receiving a zero. If probability of recording a zero is q (number of zeros/total observations), then the probability of receiving at most y-inches of precipitation within a given time series is

$$H(x) = P[\text{Precipitation Total} \le x\text{-inches}) = q + (1\text{-}q)\, F(x; k, \theta)$$

The cumulative probability, *H*(*x*), is then transformed to the standard normal random variable Z with mean zero and variance of one, which is the value of the SPI. This is an equiprobability transformation which Panofsky and Brier (1958) state has the essential feature of transforming a variate from one distribution (*i.e.*, gamma) to a variate with a distribution of prescribed form (*i.e.*, standard normal) such that the probability of being less than a given value of the variate shall be the same as the probability of being less than the corresponding value of the transformed variate. This method is illustrated in Figure 101.

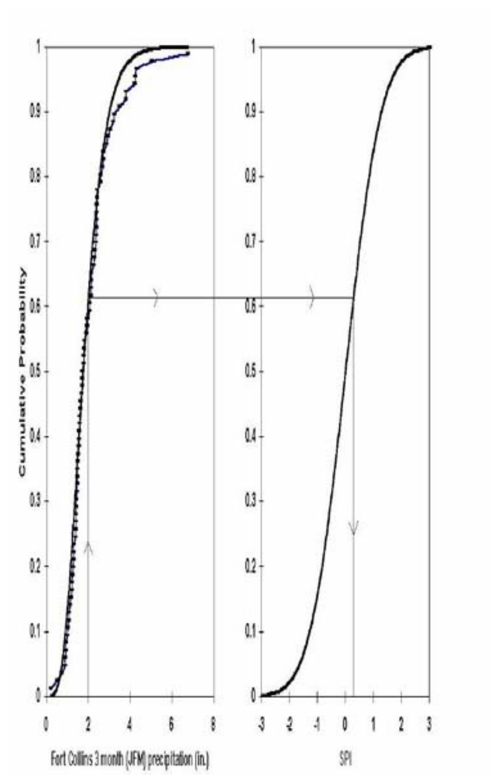

Figure 101. Equiprobability transformation.

The estimated parameters of the individual gamma distributions are given in Table 59

Table 59. Gamma Distribution Parameters

Site	Type	Parameter	Estimate	Lower 95%	Upper 95%
1	Shape	α	2.97	2.17	3.95
	Scale	σ	1.20	0.88	1.69
2	Shape	α	2.52	1.87	3.31
	Scale	σ	1.39	1.03	1.94
3	Shape	α	2.31	1.66	3.11
	Scale	σ	1.54	1.11	2.25
4	Shape	α	1.96	1.47	2.55
	Scale	σ	1.45	1.08	2.03
5	Shape	α	1.90	1.42	2.49
	Scale	σ	1.86	1.37	2.61
6	Shape	α	2.06	1.37	2.97
	Scale	σ	2.00	1.33	3.21
7	Shape	α	2.28	1.70	2.99
	Scale	σ	1.38	1.03	1.93
8	Shape	α	2.38	1.78	3.11
	Scale	σ	1.46	1.09	2.03
9	Shape	α	1.58	1.18	2.06
	Scale	σ	1.74	1.28	2.46
10	Shape	α	0.82	0.56	1.16
	Scale	σ	3.65	2.33	6.31

Fort Benning correlations

Table 60 below summarizes the daily precipitation amounts observed at the 10 Fort Benning meteorological stations. The table shows the disparencies in the number of observation observed at each site. Site 4 recorded the most precipitation amounts (2607), whereas; site 10 recorded the least (1301). The average daily precipitation ranged from a minimum of 0.0912 inches/day to a maximum of 0.1186 inches/day observed at sites 9 and 3, respectively. The maximum precipitation amounts ranged from a low of 3.4409 inches/day observed at site 4 to a maximum of 5.4449 inches/day observed at site 5. The standard deviations were consistent and do not provide any indication of any site being more variable than any other site. The standard deviations ranged from a minimum of 0.2907 to a maximum of 0.4120.

When considering the observation days where measurements were recorded at all ten (10) sampling sites, the analysis indicates that there were only 257 days were measurements were made simultaneously at each of the 10 sampling stations. Table 61 below describes the multivariate statistics for the daily precipitation amounts.

Table 60. Daily precipitation summaries (univariate statistics).

Site	N	Mean	Std Dev	Minimum	Maximum
1	2353	0.1180	0.3448	0.0000	4.8465
2	2544	0.1159	0.3455	0.0000	5.2441
3	2040	0.1186	0.3700	0.0000	4.6732
4	2607	0.0948	0.2907	0.0000	3.4409
5	2489	0.1176	0.3684	0.0000	5.4449
6	1333	0.1391	0.4120	0.0000	4.5669
7	2565	0.1047	0.3135	0.0000	3.7126
8	2603	0.1148	0.3319	0.0000	4.4094
9	2531	0.0912	0.3064	0.0000	4.5866
10	1301	0.0985	0.3113	0.0000	4.6890
Note: Statistics were calculated for each column independently without regard for missing values in other columns.					

Table 61. Daily Precipitation Summaries (Multivariate Simple Statistics).

Site	N	Mean	Std Dev	Minimum	Maximum
1	257	0.0979	0.3020	0.0000	2.6929
2	257	0.1071	0.3668	0.0000	4.2126
3	257	0.1065	0.3542	0.0000	4.0906
4	257	0.0930	0.2975	0.0000	3.0630
5	257	0.1001	0.3642	0.0000	3.8110
6	257	0.1011	0.3524	0.0000	3.3031
7	257	0.0530	0.2086	0.0000	2.3228
8	257	0.0980	0.2938	0.0000	2.5236
9	257	0.0625	0.2685	0.0000	3.3425
10	257	0.0942	0.2801	0.0000	2.4449
Note: Rows with missing values were excluded.					

When considering these 257 simultaneous measurements, the correlation measures for the amount of precipitation observed at each sampling stations are given in Table 62.

Table 62. Correlation Coefficients, N =257.

Sites	1	2	3	4	5	6	7	8	9	10
1	1.0000	0.7978	0.8612	0.8545	0.8295	0.6779	0.7926	0.8509	0.8280	0.8061
2	0.7978	1.0000	0.8729	0.8049	0.8614	0.7309	0.7927	0.7080	0.8272	0.7563
3	0.8612	0.8729	1.0000	0.8161	0.8465	0.7042	0.8154	0.7097	0.8716	0.7625
4	0.8545	0.8049	0.8161	1.0000	0.7672	0.6594	0.8102	0.7078	0.8385	0.7078
5	0.8295	0.8614	0.8465	0.7672	1.0000	0.7901	0.8614	0.6843	0.8434	0.7447
6	0.6779	0.7309	0.7042	0.6594	0.7901	1.0000	0.7529	0.5911	0.7110	0.6897
7	0.7926	0.7927	0.8154	0.8102	0.8614	0.7529	1.0000	0.6104	0.9332	0.6090
8	0.8509	0.7080	0.7097	0.7078	0.6843	0.5911	0.6104	1.0000	0.6175	0.6833
9	0.8280	0.8272	0.8716	0.8385	0.8434	0.7110	0.9332	0.6175	1.0000	0.7273
10	0.8061	0.7563	0.7625	0.7078	0.7447	0.6897	0.6090	0.6833	0.7273	1.0000
2439 rows not used due to missing or excluded values or frequency or weight variables missing, negative or less than one.										

Multivariate correlation coefficients measure the extent and the direction of the association between two variables. The square of the correlation coefficient produces the coefficient of determination or R-Square and describes the percent of the total variance explained by the linear model describing the relationship. Partial correlations, on the other hand, are defined as correlations between two variables when all others are fixed or it is the correlation between two variables adjusting for the remainder. Table 63 below, displays the partial correlation coefficients. The t-statistics given in Table 64, shows the t-values to testing the hypotheses of no relationship. With 257 observations, the critical value of the t is ± 1.96. It is readily apparent that most of the relationships between the monthly precipitation values recorded at the different sites are significant. The only exceptions are (1,7), (1,9), (2,6), (2,7), (2,9), (3,5), (3,4), (3,8), (3,10), (4,6), (4,8), (4,9), (4,10), (5,8), (6,8), (7,8), (8,10), where the ordered pair indicates the meteorological site.

Table 63. Partial Correlation, N = 257.

Sites	1	2	3	4	5	6	7	8	9	10
1	.	-0.2893	0.2598	0.3322	0.2109	-0.1953	0.1192	0.6291	0.0478	0.3449
2	-0.2893	.	0.3628	0.2545	0.3482	0.0339	-0.0384	0.2562	0.0863	0.1364
3	0.2598	0.3628	.	-0.0048	0.0951	0.0362	-0.1219	-0.0296	0.2889	-0.0406
4	0.3322	0.2545	-0.0048	.	-0.1970	0.0137	0.1303	-0.0114	0.1068	-0.0025
5	0.2109	0.3482	0.0951	-0.1970	.	0.1979	0.3642	-0.0904	-0.1483	0.1578
6	-0.1953	0.0339	0.0362	0.0137	0.1979	.	0.3804	0.0979	-0.2314	0.3919
7	0.1192	-0.0384	-0.1219	0.1303	0.3642	0.3804	.	0.0268	0.7501	-0.5633
8	0.6291	0.2562	-0.0296	-0.0114	-0.0904	0.0979	0.0268	.	-0.2362	-0.0289
9	0.0478	0.0863	0.2889	0.1068	-0.1483	-0.2314	0.7501	-0.2362	.	0.4203
10	0.3449	0.1364	-0.0406	-0.0025	0.1578	0.3919	-0.5633	-0.0289	0.4203	.

Table 64. t-Statistics for Testing (H_0: Partial Correlation = 0; H_1: Partial Correlation ≠ 0.

Sites	1	2	3	4	5	6	7	8	9	10
1		-4.82	4.29	5.61	3.44	-3.17	1.91	12.90	0.76	5.86
2	-4.82		6.20	4.19	5.92	0.54	-0.61	4.22	1.38	2.19
3	4.29	6.20		-0.08	1.52	0.58	-1.96	-0.47	4.81	-0.65
4	5.61	4.19	-0.08		-3.20	0.22	2.09	-0.18	1.71	-0.04
5	3.44	5.92	1.52	-3.20		3.22	6.23	-1.45	-2.39	2.55
6	-3.17	0.54	0.58	0.22	3.22		6.56	1.57	-3.79	6.79
7	1.91	-0.61	-1.96	2.09	6.23	6.56		0.43	18.08	-10.87
8	12.90	4.22	-0.47	-0.18	-1.45	1.57	0.43		-3.87	-0.46
9	0.76	1.38	4.81	1.71	-2.39	-3.79	18.08	-3.87		7.38
10	5.86	2.19	-0.65	-0.04	2.55	6.79	-10.87	-0.46	7.38	

Standardized precipitation indices.

According to the Western Regional Climate Center (http://www.wrcc.dri.edu/ spi/explanation.html), the standardized precipitation index (SPI), first proposed by Tom Mckee and others in 1993, is an index used to assign a single numeric value to precipitation totals so that comparison across regions with markedly different climate regimes can be performed. The SPI is an index value that represents the number of standard deviations that the observed value deviates from a long-term mean, for a normally distributed random variable. Since precipitation totals appear to follow a gamma distribution the equiprobability transformation is first applied so that the transformed precipitation values follow a normal distribution. The SPI can explicitly express the fact that it is possible to simultaneously experience wet and dry conditions at various time scales. Separate SPI values are calculated for a selection of time scales, covering 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 15, 18, 24, 30, 36, 48, 60, and 72 months, and ending on the last day of the latest month. For this report, only two time scales are considered – 1 and 3 months.

The algorithm first fits a time series of interest to the accumulated precipitation value of interest. Then, a frequency distribution is selected and a statistical fit to the data is determined. The cumulative distribution is formed from the fitted frequency distribution. The percentile for the particular time series element of interest, usually the latest one, is selected from the cumulative distribution. Following McKee et al. (1993, 1995), we have chosen to use the gamma distribution (see, for example, Wilks, 1995, p 95-97). This distribution is very robust and can deal with the wide range of extreme climates, especially those where monthly and seasonal precipitation of zero is common and expected.

Table 65 below displays the SPI values for the sampling year of 2006 and compares the index values for Fort Benning to Columbus Metropolitan airport and the five climate regions surrounding Fort Benning (three in Alabama and two in Georgia). The time series of interest were selected as 1 month and 3 months and only cover a historical span from 1999 to 2006. It is highly recommended that at least twenty-five years, if not more, before SPI values should be computed; however, with only limited data such as what was observed at Fort Benning, these SPI values should only be considered for correlative measure only. SPI values are interpreted as follows:

+3.0 and above exceptionally wet
+2.00 to +2.99 extremely wet
+1.25 to +1.99 very wet
+0.75 to +1.24 moderately wet
-0.74 to +0.74 near normal
-1.24 to –0.75 moderately dry
-1.99 to –1.25 very dry
-2.99 to – 2.00 extremely dry
-3.00 and belowexceptionally dry

The complete history, 1999-2006, SPI values are given in Appendix III.

Table 65. Standardized Precipitation Indices (Time Series = 1 Month, Year = 2006).

	Fort Benning		Alabama Climate Regions						Georgia Climate Regions				Columbus Airport	
	SPI - 1	SPI-3	SPI - 1	SPI-3	SPI - 1	SPI-3	SPI - 1	SPI-I3	SPI - 1	SPI-3	SPI - 1	SPI-3	SPI - 1	SP-3
1	0.58	-0.03	0.97	-0.12	0.89	-0.92	1.02	-0.31	0.44	-0.06	1.56	1.30	0.31	0.64
2	0.52	0.42	0.47	1.24	0.37	0.37	0.45	0.44	0.49	0.72	0.60	1.58	0.52	0.30
3	-0.56	-0.89	-0.40	0.07	-0.54	-0.10	-1.00	-0.77	-0.64	-0.56	-1.12	-0.97	-0.66	-0.86
4	-0.63	-0.95	-0.88	-0.53	-0.94	-0.79	-1.30	-1.28	-0.70	-0.64	-0.93	-1.31	-0.26	-0.76
5	0.43	-0.94	-0.36	-0.76	0.42	-0.77	0.94	-0.87	-0.37	-0.90	0.97	-0.89	0.28	-0.75
6	-1.48	-0.70	-1.06	-0.86	-1.58	-0.86	-1.82	-1.07	-0.96	-0.80	-1.86	-1.04	-0.88	-0.43
7	-0.27	-0.63	-0.53	-0.76	-0.86	-0.79	-0.32	-0.70	-0.84	-0.87	-0.84	-1.05	-0.66	-0.67
8	-0.86	-1.21	-0.62	-0.91	-0.11	-1.07	0.27	-0.95	0.47	-0.77	0.31	-1.23	0.26	-0.84
9	-0.57	-1.12	0.34	-0.69	-1.21	-1.26	-1.20	-0.82	0.18	-0.60	-0.07	-1.13	0.18	-0.34
10	0.44	-0.92	1.53	0.77	1.00	-0.07	0.90	0.13	0.63	0.42	0.96	0.29	1.01	0.48
11	0.53	-0.10	0.28	0.72	0.24	0.15	0.11	0.07	0.26	0.30	-0.13	0.15	0.59	0.60
12	0.13	0.42	-0.79	0.64	0.04	0.64	0.56	0.72	-0.25	0.31	0.87	0.76	0.05	0.79

Table 66 displays the correlation coefficients between the SPI values observed at Fort Benning and the other areas of interest. Table 66 values represent relationship between the indices computed at 1-month intervals. As can be seen from this table, the correlation coefficients are exceptionally good with the smallest being 0.7075 and the largest being 0.9032. This gives a good indication of the relationship between the drought/wet conditions observed at Fort Benning and those of the surrounding area.

Table 66. Multivariate Correlations (Sampling Dates – August, 1999 through December, 2006, SPI – Run Length of 1 Month).

	FB-SPI-1	A05-SPI-1	A06-SPI-1	A07-SPI-1	G04-SPI-1	G07-SPI-1	CGA-SPI-1
FB-SPI-1	1.0000	0.7733	0.7481	0.8020	0.8752	0.8681	0.9032
A05-SPI-1	0.7733	1.0000	0.8689	0.8217	0.8885	0.7387	0.7679
A06-SPI-1	0.7481	0.8689	1.0000	0.9173	0.7731	0.7285	0.7075
A07-SPI-1	0.8020	0.8217	0.9173	1.0000	0.7849	0.8481	0.7589
G04-SPI-1	0.8752	0.8885	0.7731	0.7849	1.0000	0.8272	0.8881
G07-SPI-1	0.8681	0.7387	0.7285	0.8481	0.8272	1.0000	0.8369
CGA-SPI-1	0.9032	0.7679	0.7075	0.7589	0.8881	0.8369	1.0000

Note: FB – Fort Benning
A05 – Alabama Climate Region 05
A06 – Alabama Climate Region 06
A07 – Alabama Climate Region 07
G04 – Georgia Climate Region 04
G07 – Georgia Climate Region 07
CGA- Columbus Metropolitan Airport

Table 67 below shows the correlation coefficients between the SPI values of the same areas as Table 66; however, the correlations are computed on the SPI values on the 3-month time series. A 3-month time series represents a seasonal time series and shows potential changes over seasons.

Table 67. Multivariate Correlations (Sampling Dates – August, 1999 through December, 2006); SPI – Run Length of 3 Months

Table 67. Correlation coefficients computed on the SPI values on the 3-month time series.

	FB-SPI-3	A05-SPI-3	A06-SPI-3	A07-SPI-3	G04-SPI-3	G07-SPI-3	CGA-SPI-3
FB-SPI-3	1.0000	0.8390	0.7630	0.8260	0.9292	0.9006	0.9075
A05-SPI-3	0.8390	1.0000	0.8364	0.8547	0.9090	0.8403	0.8431
A06-SPI-3	0.7630	0.8364	1.0000	0.9349	0.7531	0.7104	0.7322
A07-SPI-3	0.8260	0.8547	0.9349	1.0000	0.8243	0.8050	0.8037
G04-SPI-3	0.9292	0.9090	0.7531	0.8243	1.0000	0.9187	0.9027
G07-SPI-3	0.9006	0.8403	0.7104	0.8050	0.9187	1.0000	0.9053
CGA-SPI-3	0.9075	0.8431	0.7322	0.8037	0.9027	0.9053	1.0000

2 rows not used due to missing or excluded values or frequency or weight variables missing, negative or less than one.

Note: FB – Fort Benning

A05 – Alabama Climate Region 05

A06 – Alabama Climate Region 06

A07 – Alabama Climate Region 07

G04 – Georgia Climate Region 04

G07 – Georgia Climate Region 07

CGA- Columbus Metropolitan Airport

As with Table 65, the correlations are extremely good with the minimum being 0.7104 to a maximum of 0.9349. The historical SPI values for the surround area and their associated correlations are given in Tables 15 through 17. Historically, the 1-month time series SPI values for Columbus Airport ranged from a minimum of –1.04 to a maximum of +0.7 during 2006; whereas, for the 1999-2006 sampling years, the SPI values ranged from a minimum of –0.88 to a maximum of +1.07. For the 3-month SPI time series values, historically the 2006 ranged from a minimum of –1.19 to +0.67; whereas, the 3-month data ranging from 1990-2006 produced SPI values ranging from a minimum of –0.86 to a maximum of +0.79. The correlation structures given in Tables 68 and 69 show similar relations for the historical period as do the period from 1999-2006.

Table 68. 2006 SPI Values for surrounding areas, history: 1948 – 2007.

	Columbus Airport		Alabama Climate Regions						Georgia Climate Regions			
			05		06		07		04		07	
Mo	SPI-1	SPI-3	SPI-1	SPI-3	SPI-1	SPI-3	SPI-1	SPI-3	SPI-1	SPI-3	SPI-1	SPI-3
1	-0.46	-0.31	0.46	0.01	0.31	-0.38	0.01	-0.23	-0.08	-0.26	0.23	0.33
2	0.15	-0.85	0.04	-0.11	0.35	-0.19	0.01	-0.48	0.05	-0.50	0.09	0.14
3	-0.98	-1.01	-0.53	-0.20	-0.71	-0.22	-1.64	-1.03	-0.99	-0.75	-1.91	-0.88
4	-0.25	-0.93	-0.45	-0.67	-0.82	-0.82	-1.28	-1.73	-0.56	-0.99	-0.72	-1.46
5	-0.02	-1.06	0.05	-0.71	0.54	-0.73	0.63	-1.24	-0.41	-1.27	0.47	-1.27
6	-1.01	-0.84	-0.89	-0.78	-1.02	-0.75	-1.50	-1.04	-0.89	-1.15	-1.20	-0.91
7	-1.04	-1.19	-0.29	-0.72	-1.49	-0.97	-0.61	-0.81	-1.15	-1.42	-1.02	-1.01
8	0.15	-1.12	-0.30	-0.93	0.43	-1.12	0.67	-0.79	0.18	-1.19	0.24	-1.20
9	0.29	-0.61	0.46	-0.17	-0.43	-0.95	-0.66	-0.48	0.40	-0.52	0.23	-0.42
10	0.70	0.41	0.92	0.57	0.95	0.40	1.23	0.64	0.48	0.45	0.74	0.48
11	0.63	0.67	0.85	0.98	0.88	0.66	0.76	0.66	0.72	0.66	0.32	0.45
12	-0.60	0.24	-0.72	0.53	-0.29	0.77	0.14	1.05	-0.71	0.14	0.31	0.52

Table 69. 1-Month SPI Correlation Coefficients (1948 - 2007)

		Columbus Airport	Alabama Climate Region			Georgia Climate Region	
			05	06	07	04	07
Columbus Airport		1	0.7641	0.6975	0.7173	0.8320	0.7079
Alabama Climate Region	05	0.7641	1	0.8723	0.8015	0.8879	0.6951
	06	0.6975	0.8723	1	0.8687	0.7826	0.6701
	07	0.7173	0.8015	0.8687	1	0.7648	0.8024
Georgia Climate Region	04	0.8320	0.8879	0.7826	0.7648	1	0.7608
	07	0.7079	0.6951	0.6701	0.8024	0.7608	1

Table 16. Three -Month Correlation Coefficients (1948-2007).

		Columbus Airport	Alabama Climate Region			Georgia Climate Region	
			05	06	07	04	07
Columbus Airport		1	0.7554	0.6920	0.6949	0.8336	0.6986
Alabama Climate Region	05	0.7554	1	0.8820	0.8148	0.8963	0.7007
	06	0.6920	0.8820	1	0.8751	0.7892	0.6529
	07	0.6949	0.8148	0.8751	1	0.7762	0.7906
Georgia Climate Region	04	0.8336	0.8963	0.7892	0.7762	1	0.7880
	07	0.6986	0.7007	0.6529	0.7906	0.7880	1

Conclusion

Summaries of the meteorological data are presented in this report for research purposes only. Correlation structures provide insight into the relationship and interdependent structures of multivariable studies. These structures provide us with an understanding of the important cause-effect relationships; however, one must be cautious in these interpretations as studies such as these are not designed as cause-effect studies, but more of an association among the constituents.

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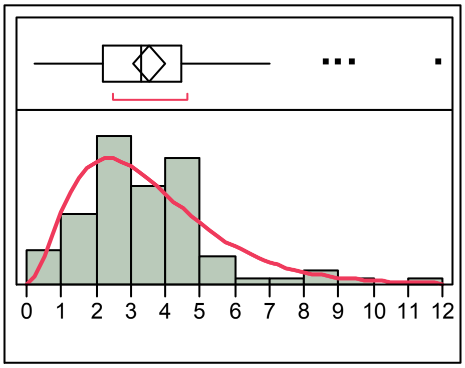
Appendix I: Distributions

Distributions

Site=1, monthly precipitation (inches)



Fitted gamma, parameter estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Shape	α	2.9679479	2.1731907	3.9463645
Scale	σ	1.1990105	0.8820383	1.6923394

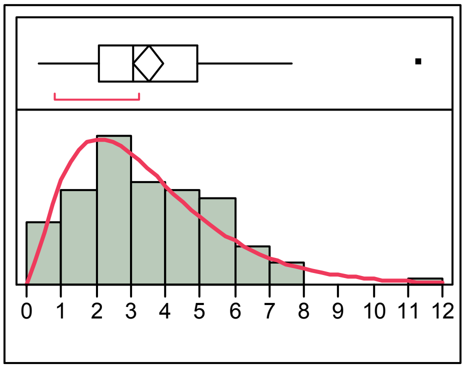
Quantiles

100.0%	Maximum	11.886
99.5%		11.886
97.5%		9.433
90.0%		5.469
75.0%	Q3	4.438
50.0%	Median	3.285
25.0%	Q1	2.184
10.0%		1.377
2.5%		0.348
0.5%		0.260
0.0%	Minimum	0.260

Moments

Mean	3.5586008
Std Dev	2.0361939
Std Err Mean	0.2305536
Upper 95% Mean	4.0176916
Lower 95% Mean	3.0995101
N	78

Site=2, monthly precipitation (inches)



Fitted gamma, parameter estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Shape	α	2.5220303	1.8738532	3.3136271
Scale	σ	1.3918407	1.0329197	1.9438606

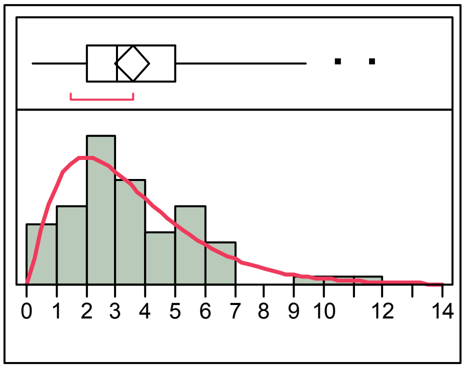
Quantiles

100.0%	Maximum	11.295
99.5%		11.295
97.5%		7.633
90.0%		6.317
75.0%	Q3	4.906
50.0%	Median	3.093
25.0%	Q1	2.074
10.0%		1.024
2.5%		0.347
0.5%		0.319
0.0%	Minimum	0.319

Moments

Mean	3.5102643
Std Dev	2.0613469
Std Err Mean	0.2249114
upper 95% Mean	3.957604
lower 95% Mean	3.0629247
N	84

Site=3, monthly precipitation (inches)



Fitted gamma, parameter estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Shape	α	2.3057671	1.6578873	3.1145659
Scale	σ	1.5436453	1.1088605	2.2478786

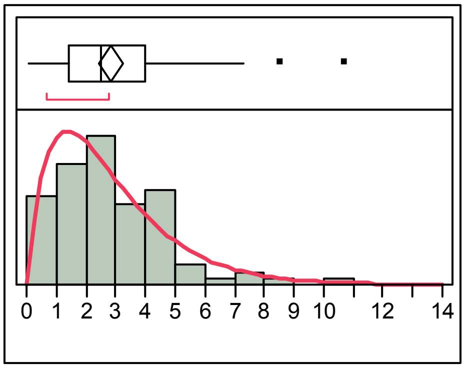
Quantiles

100.0%	Maximum	11.642
99.5%		11.642
97.5%		10.794
90.0%		6.591
75.0%	Q3	5.005
50.0%	Median	3.065
25.0%	Q1	2.037
10.0%		0.897
2.5%		0.261
0.5%		0.181
0.0%	Minimum	0.181

Moments

Mean	3.5592867
Std Dev	2.2876119
Std Err Mean	0.2774137
Upper 95% Mean	4.1130067
Lower 95% Mean	3.0055667
N	68

Site=4, monthly precipitation (inches)



Fitted gamma, parameter estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Shape	α	1.9559611	1.4681859	2.5489878
Scale	σ	1.4519642	1.078888	2.0263666

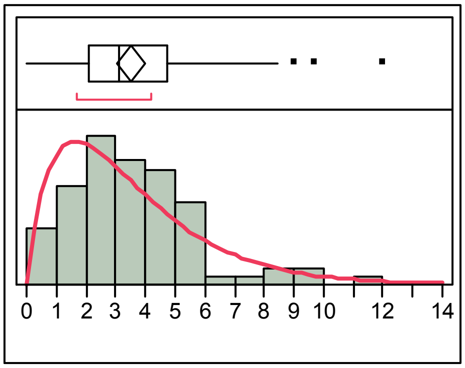
Quantiles

100.0%	Maximum	10.654
99.5%		10.654
97.5%		8.261
90.0%		4.953
75.0%	Q3	4.024
50.0%	Median	2.516
25.0%	Q1	1.433
10.0%		0.655
2.5%		0.192
0.5%		0.087
0.0%	Minimum	0.087

Moments

Mean	2.8399855
Std Dev	1.9093739
Std Err Mean	0.2047064
Upper 95% Mean	3.2469283
Lower 95% Mean	2.4330427
N	87

Site=5, monthly precipitation (inches)



Fitted gamma, parameter estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Shape	α	1.8999688	1.4169195	2.4898939
Scale	σ	1.8565156	1.369596	2.6149377

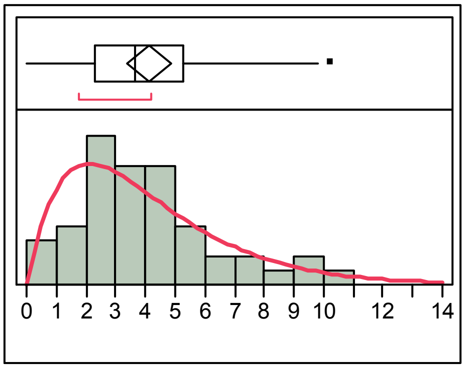
Quantiles

100.0%	Maximum	11.949
99.5%		11.949
97.5%		9.606
90.0%		5.811
75.0%	Q3	4.701
50.0%	Median	3.083
25.0%	Q1	2.087
10.0%		1.154
2.5%		0.177
0.5%		0.00394
0.0%	Minimum	0.00394

Moments

Mean	3.5273219
Std Dev	2.2122035
Std Err Mean	0.2428209
Upper 95% Mean	4.01037
Lower 95% Mean	3.0442738
N	83

Site=6, monthly precipitation (inches)



Fitted gamma, parameter estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Shape	α	2.0628474	1.3735373	2.9676039
Scale	σ	1.9974683	1.3343492	3.2063405

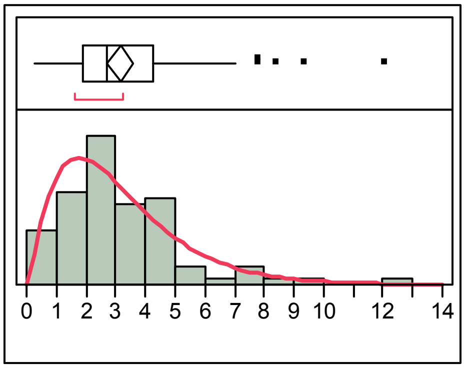
Quantiles

100.0%	Maximum	10.189
99.5%		10.189
97.5%		10.135
90.0%		8.032
75.0%	Q3	5.309
50.0%	Median	3.665
25.0%	Q1	2.266
10.0%		1.815
2.5%		0.068
0.5%		0.031
0.0%	Minimum	0.031

Moments

Mean	4.1204724
Std Dev	2.4218364
Std Err Mean	0.3610261
Upper 95% Mean	4.8480726
Lower 95% Mean	3.3928722
N	45

Site=7, monthly precipitation (inches)



Fitted gamma, parameter estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Shape	α	2.2825457	1.7021406	2.9902893
Scale	σ	1.3848371	1.0280918	1.9338161

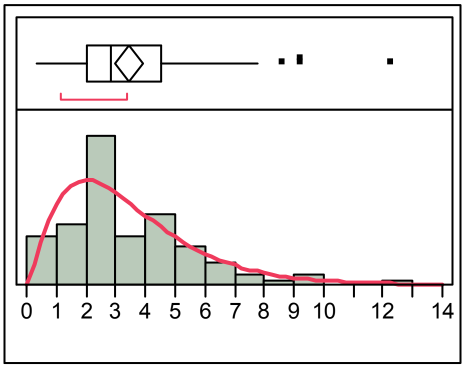
Quantiles

100.0%	Maximum	12.047
99.5%		12.047
97.5%		9.213
90.0%		5.861
75.0%	Q3	4.232
50.0%	Median	2.720
25.0%	Q1	1.904
10.0%		0.963
2.5%		0.298
0.5%		0.280
0.0%	Minimum	0.280

Moments

Mean	3.1609541
Std Dev	2.1000307
Std Err Mean	0.2277803
Upper 95% Mean	3.6139203
Lower 95% Mean	2.707988
N	85

Site=8, monthly precipitation (inches)



Fitted gamma, parameter estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Shape	α	2.3792606	1.7760552	3.1140716
Scale	σ	1.4607321	1.0868323	2.0338817

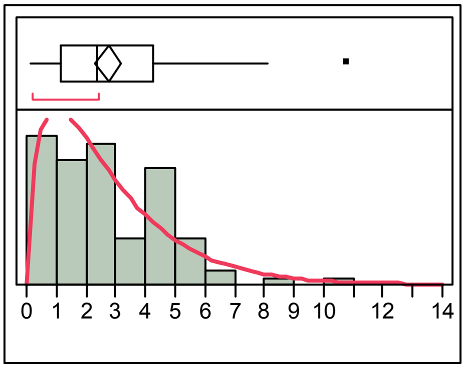
Quantiles

100.0%	Maximum	12.256
99.5%		12.256
97.5%		9.187
90.0%		6.098
75.0%	Q3	4.560
50.0%	Median	2.868
25.0%	Q1	2.038
10.0%		0.969
2.5%		0.366
0.5%		0.315
0.0%	Minimum	0.315

Moments

Mean	3.4754624
Std Dev	2.2396713
Std Err Mean	0.24151
Upper 95% Mean	3.9556489
Lower 95% Mean	2.9952759
N	86

Site=9, monthly precipitation (inches)



Fitted gamma, parameter estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Shape	α	1.5781945	1.1839352	2.0585553
Scale	σ	1.7416065	1.2821961	2.4613844

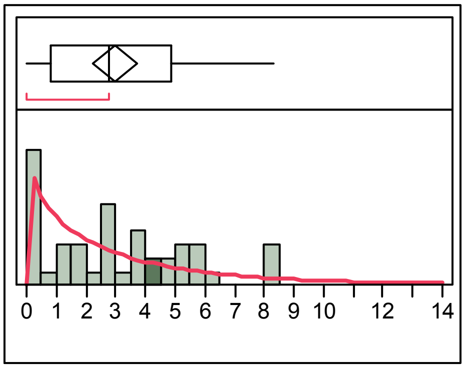
Quantiles

100.0%	Maximum	10.748
99.5%		10.748
97.5%		7.938
90.0%		5.295
75.0%	Q3	4.239
50.0%	Median	2.358
25.0%	Q1	1.128
10.0%		0.427
2.5%		0.225
0.5%		0.126
0.0%	Minimum	0.126

Moments

Mean	2.7485939
Std Dev	2.0249323
Std Err Mean	0.2209382
Upper 95% Mean	3.1880312
Lower 95% Mean	2.3091567
N	84

Site=10, monthly precipitation (inches)



Fitted gamma, parameter estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Shape	α	0.8165919	0.5562308	1.1562072
Scale	σ	3.6481295	2.3265274	6.309825

Quantiles

100.0%	Maximum	8.3425
99.5%		8.3425
97.5%		8.3421
90.0%		5.9181
75.0%	Q3	4.8780
50.0%	Median	2.7756
25.0%	Q1	0.7874
10.0%		0.0858
2.5%		0.0134
0.5%		0.0118
0.0%	Minimum	0.0118

Moments

Mean	2.9790331
Std Dev	2.4057462
Std Err Mean	0.3668729
upper 95% Mean	3.7194125
lower 95% Mean	2.2386538
N	43

Appendix II: Standardized precipitation indices

		Fort Benning		Alabama Climate Regions						Georgia Climate Regions				Columbus Airport	
Year	Month	SPI - 1	SPI-3	SPI - 1	SPI-3	SPI - 1	SPI-3	SPI - 1	SPI-3	SPI - 1	SPI-3	SPI - 1	SPI-3	SPI - 1	SPI-3
2003	1	-1.66	1.23	-1.19	0.51	-1.71	0.45	-2.07	0.41	-1.36	1.12	-1.82	0.80	-1.28	0.62
2003	2	0.88	1.49	0.97	1.63	0.66	1.23	0.92	1.22	0.98	1.86	0.93	0.88	1.00	1.55
2003	3	0.09	-0.20	0.10	-0.11	-0.29	-0.70	0.38	0.31	0.36	0.47	0.57	0.92	0.19	0.38
2003	4	1.19	0.77	1.45	0.79	1.74	1.13	1.07	0.98	1.26	0.95	1.25	1.27	0.79	0.72
2003	5	1.03	0.69	2.14	1.41	1.73	1.44	1.59	1.13	1.98	1.33	1.02	1.05	1.37	0.74
2003	6	0.83	1.11	1.38	1.88	1.36	1.89	0.93	1.44	1.34	1.67	0.18	1.07	1.10	1.16
2003	7	1.11	1.19	1.24	1.78	1.20	1.56	1.34	1.60	0.90	1.51	1.11	1.06	1.33	1.30
2003	8	1.39	1.28	1.06	1.40	1.09	1.31	1.01	1.32	0.89	1.25	1.47	1.05	0.47	1.17
2003	9	-0.28	0.86	-0.52	0.90	-0.17	1.01	-0.41	1.00	-0.49	0.40	-0.79	0.61	-0.42	0.71
2003	10	0.51	0.53	-1.46	-0.64	-0.50	0.18	-0.56	-0.21	-0.29	-0.32	0.84	0.36	0.85	0.05
2003	11	-0.83	-0.48	0.53	-0.32	0.08	-0.43	-0.28	-0.79	0.07	-0.48	-0.75	-0.50	-0.36	-0.35
2003	12	-0.37	-0.43	-1.17	-0.50	-1.26	-0.81	-0.42	-0.79	-0.36	-0.27	-0.92	-0.28	0.19	0.15
2004	1	1.18	-0.25	-1.13	-0.84	-0.66	-1.09	-0.30	-0.56	-0.61	-0.61	0.06	-0.97	0.06	-0.31
2004	2	0.89	1.17	0.79	-1.37	1.13	0.25	1.54	1.22	0.79	0.27	1.21	0.75	0.75	0.79
2004	3	-2.06	-1.25	-1.85	-1.74	-1.86	-0.95	-1.67	-0.55	-1.96	-1.63	-1.82	-1.39	-1.98	-1.61
2004	4	-0.21	-1.23	-0.61	-1.06	-0.59	-0.69	-0.20	-0.38	-0.72	-1.11	-0.65	-0.92	-0.11	-1.18
2004	5	0.59	-1.44	0.08	-1.14	0.44	-1.21	0.09	-1.09	-0.03	-1.36	0.20	-1.45	0.19	-1.35
2004	6	0.68	0.44	0.06	-0.15	0.91	0.21	1.19	0.62	0.37	0.00	1.18	0.51	0.44	0.24
2004	7	-0.02	0.43	-0.14	-0.05	-0.30	0.32	-0.34	0.49	-0.41	-0.02	-0.65	0.42	0.10	0.20
2004	8	0.70	0.41	0.80	0.06	0.59	0.30	0.05	0.43	0.24	-0.01	0.26	0.37	1.05	0.39
2004	9	1.97	1.51	1.59	1.01	1.31	0.31	1.67	0.38	1.76	1.27	1.59	1.38	1.75	1.49
2004	10	-0.43	2.08	0.72	1.94	0.35	1.18	0.66	1.31	0.15	1.79	0.04	1.69	-0.47	2.10
2004	11	1.37	1.93	1.07	1.48	1.55	1.63	1.49	1.67	1.15	1.60	1.14	1.50	1.06	1.81
2004	12	-0.66	0.24	0.11	1.15	-0.55	0.94	-0.29	1.02	-0.90	0.45	-0.38	0.24	-0.21	0.42
2005	1	-0.64	0.32	-0.91	0.64	-0.90	0.71	-0.57	0.89	-0.77	0.35	-0.27	0.27	-0.50	0.78
2005	2	0.64	-0.22	0.74	-0.31	0.61	-0.38	0.05	-0.51	0.86	-0.01	0.13	-0.39	0.79	0.50
2005	3	0.65	1.12	0.84	0.72	0.84	0.90	0.40	0.05	0.70	1.00	0.86	1.37	0.76	1.26
2005	4	1.61	1.47	1.45	1.25	1.17	1.32	1.77	1.12	1.76	1.34	1.65	1.43	1.83	1.65
2005	5	-0.08	1.05	-0.24	0.80	-0.21	1.03	-0.39	0.93	0.08	0.90	0.37	1.27	1.08	1.48
2005	6	0.70	0.86	0.13	0.39	0.62	0.76	0.34	0.91	1.04	0.97	0.68	1.30	1.11	1.34
2005	7	1.48	1.01	1.69	0.72	1.66	1.05	1.36	0.78	1.88	1.22	1.74	1.44	1.51	1.31
2005	8	1.33	1.41	1.79	1.27	0.90	1.26	1.52	1.19	1.59	1.73	1.49	1.60	1.62	1.52
2005	9	-1.79	0.69	-1.51	1.25	-0.06	1.35	0.03	1.36	-1.88	1.20	-1.44	0.88	-1.77	0.98
2005	10	-0.49	-0.73	-0.48	-0.44	-1.59	-0.34	-1.58	0.03	-0.08	-0.37	-0.91	-0.68	-0.45	-0.24
2005	11	-0.05	-1.27	-0.48	-1.14	-1.13	-1.55	-0.50	-0.99	-0.15	-1.01	0.20	-1.21	0.81	-0.73
2005	12	-0.30	-0.46	-0.19	-0.79	-0.86	-1.94	-0.55	-1.33	0.03	-0.19	0.78	0.05	-0.42	0.15
2006	1	0.58	-0.03	0.97	-0.12	0.89	-0.92	1.02	-0.31	0.44	-0.06	1.56	1.30	0.31	0.64
2006	2	0.52	0.42	0.47	1.24	0.37	0.37	0.45	0.44	0.49	0.72	0.60	1.58	0.52	0.30
2006	3	-0.56	-0.89	-0.40	0.07	-0.54	-0.10	-1.00	-0.77	-0.64	-0.56	-1.12	-0.97	-0.66	-0.86
2006	4	-0.63	-0.95	-0.88	-0.53	-0.94	-0.79	-1.30	-1.28	-0.70	-0.64	-0.93	-1.31	-0.26	-0.76
2006	5	0.43	-0.94	-0.36	-0.76	0.42	-0.77	0.94	-0.87	-0.37	-0.90	0.97	-0.89	0.28	-0.75
2006	6	-1.48	-0.70	-1.06	-0.86	-1.58	-0.86	-1.82	-1.07	-0.96	-0.80	-1.86	-1.04	-0.88	-0.43
2006	7	-0.27	-0.63	-0.53	-0.76	-0.86	-0.79	-0.32	-0.70	-0.84	-0.87	-0.84	-1.05	-0.66	-0.67
2006	8	-0.86	-1.21	-0.62	-0.91	-0.11	-1.07	0.27	-0.95	0.47	-0.77	0.31	-1.23	0.26	-0.84

		Fort Benning		Alabama Climate Regions						Georgia Climate Regions				Columbus Airport	
2006	9	-0.57	-1.12	0.34	-0.69	-1.21	-1.26	-1.20	-0.82	0.18	-0.60	-0.07	-1.13	0.18	-0.34
2006	10	0.44	-0.92	1.53	0.77	1.00	-0.07	0.90	0.13	0.63	0.42	0.96	0.29	1.01	0.48
2006	11	0.53	-0.10	0.28	0.72	0.24	0.15	0.11	0.07	0.26	0.30	-0.13	0.15	0.59	0.60
2006	12	0.13	0.42	-0.79	0.64	0.04	0.64	0.56	0.72	-0.25	0.31	0.87	0.76	0.05	0.79

SERDP ecosystem characterization and monitoring initiative

White paper C6: Linear relationships between total suspended solids (mg/L) and turbidity (NTU) (A. Dale Magoun, Ph.D., Applied Research and Analysis, Inc.)

Purpose and scope

The purpose and score of this data report is to describe the relationship between total suspended solids (TSS) concentrations and turbidity. These parameters both indicate the amount of solids suspended in the water, whether mineral (e.g., soil particles) or organic (e.g., algae) and provide an estimation of erosion as a result of storm events. TSS tests measure and the actual weight of the material per volume of water, whereas, turbidity measures the amount of light scattered from a water sample (more suspended particles cause greater scattering). The difference in estimating techniques used to determine the concentrations of suspended material becomes important as calculations to determine actual concentration of particulate matter are possible with TSS values, but not with turbidity readings. Measuring turbidity, however, is less time consuming and can be done *in-situ*, whereas, TSS is a laboratory procedure. Thus, using turbidity to predict TSS in streams and rivers has been the topic of much research in recent years.

Literature review

In 2005, H.G. Earhart published a paper entitled “Monitoring total suspended solids by using nephelometry” where he described the correlation structure of the two measures. In his abstracted Earhart stated “Correlation curves were developed relating nephelometric turbidity units (NTU) with total suspended solids (TSS) for diked upland dredged material placement site effluents of three US Army Corps of Engineers (COE) maintenance dredging projects in the Chesapeake Bay, Maryland. The procedure was developed in an effort to ensure compliance with Maryland's 400 milligrams per liter (mg/l) TSS standard for COE dredging projects. Samples of the sediments to be dredged were collected and analyzed, correlating turbidity readings with TSS determined by standard gravimetric techniques. The correlation curves were provided to the COE inspectors to measure the effluent with a turbidity meter and to extract a TSS concentration from the correlation curve. Samples collected and analyzed after initiation of the dredging indicated that the correlation curves were an overestimate of the actual TSS concentrations of the effluent discharges. The procedure, endorsed by the State of Maryland, provided immediate on-site TSS analysis eliminating the previously encountered delays in obtaining gravimetric analysis of effluent discharges and potential contract management problems." Packman (10) described the relationship using Log Linear models; whereas, other researchers have used Linear models relating Turbidity and TSS. In either case, the models are linear and can be expressed as

Log Linear: LN(TSS) = Intercept + Slope * LN(Turbidity)

Linear: TSS = Intercept + Slope * Turbidty

Packman stated "We investigated whether turbidity could produce a satisfactory estimate of TSS in urbanizing streams of the Puget Lowlands. A log-linear model showed strong positive correlation between TSS and turbidity (R_2 = 0.96) with a regression equation of ln(TSS) = 1.32 ln(NTU) + C, with C not significantly different than 0 for 8 of the 9 sampled streams. These results strongly suggest that turbidity is a suitable monitoring parameter where water-quality conditions must be evaluated, however logistical and/or financial constraints make an intensive program of TSS sampling impractical." Packman's paper reported on the analysis of two areas – Rutherford Creek and other water bodies. The Rutherford creek model indicated that the slope of the log-linear model was 1.32 with an intercept of – 0.68; whereas, with the other creeks, the slope remained the same, 1.32, but the intercept changed to 0.15. Figure 102 below displays the relationship found by Packman.

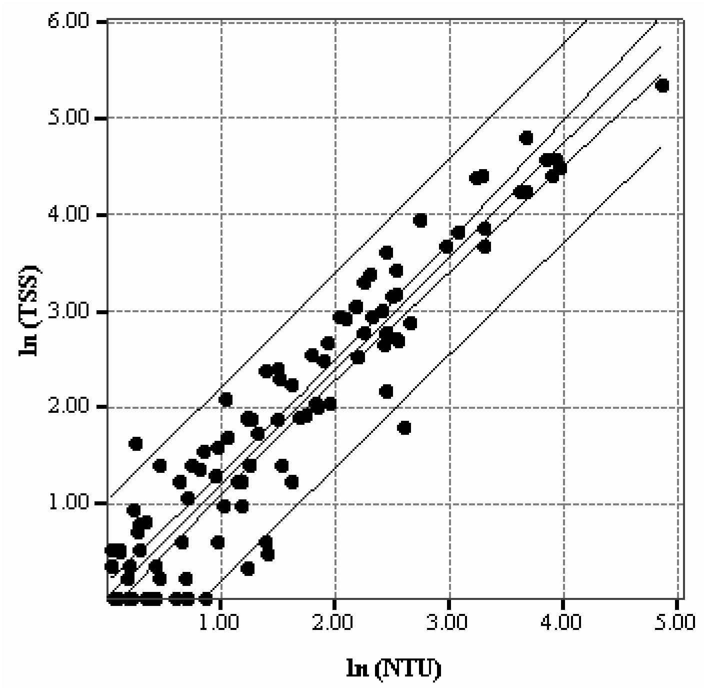


Figure 102. The relationship found by Packman.

In a publication by Hach (11), their researchers developed as a laboratory experiment a model that relates the two measures. Their data indicated a linear relationship whose R-Square was 0.98 and is show below:

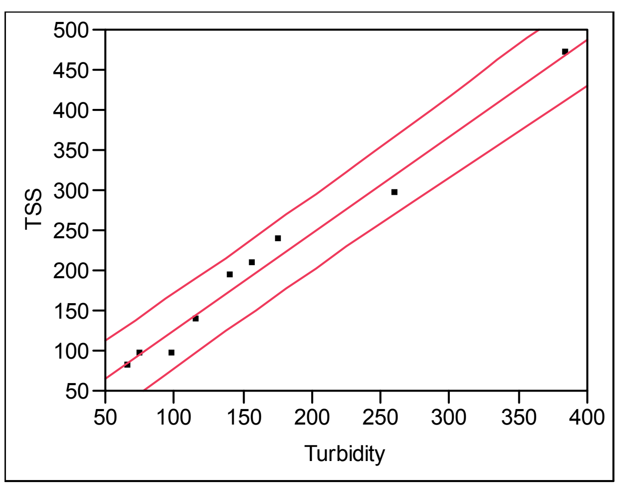


Figure 103. Bivariate Fit of TSS By Turbidity.

Table 70. Linear Fit, Model: TSS = 3.1669013 + 1.2126227*Turbidity, Summary of Fit.

R-Square	0.980888
RSquare Adj	0.978157
Root Mean Square Error	18.38922
Mean of Response	201.2556
Observations (or Sum Wgts)	9

Table 71. Parameter estimates.

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	3.1669013	12.116	0.26	0.8013
Turbidity	1.2126227	0.063977	18.95	<.0001

Fort Benning data.

In a study conducted by the Corp of Engineers at the Army installation at Fort Benning, GA, scientists collected data during and after storm events at four creeks – North Randall, Tiger Creek, North Upatoi and Pine Knot. The data was collected in late 2005 and spring of 2006. Table 1 of Appendix I displays the data collected during storm events on the Fort Benning training grounds.

Models

As mentioned in the literature review section, there appears to be two models that are consistently used to describe the relationship between turbidity and suspended solids. Laboratory experiments indicate that a linear relationship fits the data extremely well; however, one must be cautious of the fact that laboratory is very rarely replicated in field experiments and that scientific field data rarely obeys a linear relationship. However, both models were examined and interpreted for potential use.

Linear model

Analysis of these data is given below. Figure 104 describes the linear relationship between TSS and Turbidity. The analysis indicates that the linear model explained 40.8% of the total variance (R-Square) and that the regression model which best describes this linear relationship is

$$\text{TSS} = 59.921 + 0.511 * \text{Turbidity}$$

Both parameters were significant (see Table 2) and there appeared to be no lack of fit (F = 0.4523, p-value = 0.9978).

Table 72. Parameter estimates.

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	59.920633	24.03599	2.49	0.0139
Turbidity	0.5113436	0.054442	9.39	<.0001

Figure 104 displays a plot depicting the model fit and the confidence bands for predicting individual values of TSS.

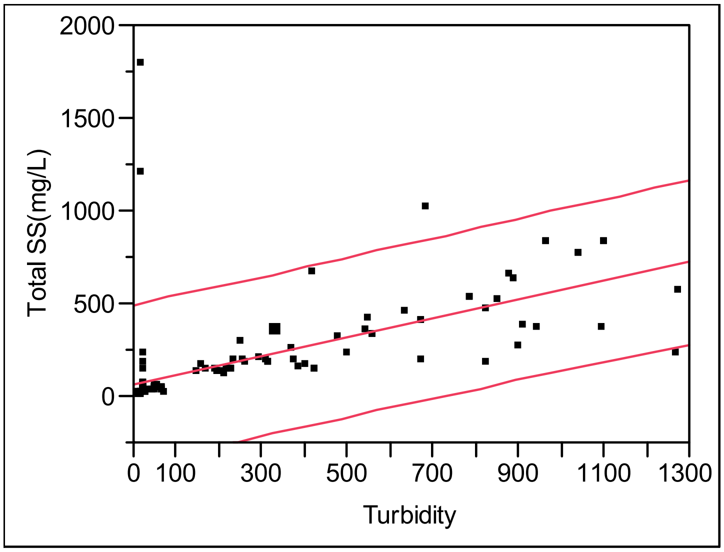


Figure 104. Bivariate fit of total SS (mg/L) By turbidity.

Whereas, the model seems to fit well, the low R-Square leads one to believe that this may not be the most appropriate model for this set of field data.

Log-log model

Figure 105 describes the log-linear relationship between log(TSS) and log(Turbidity). The analysis indicates that the log-linear model explained 70.4% of the total variance (R-Square) and that the regression model which best describes this log-log relationship is

$$\text{Log(TSS)} = 0.8367 + 0.7778 * \text{Log(Turbidity)}$$

Both parameters were significant (see Table 3) and there appeared to be no lack of fit (F = 0.6183, p-value = 0.9562).

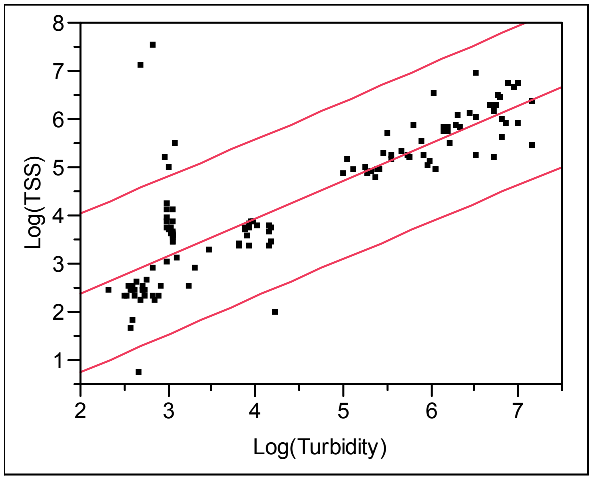


Figure 105. Bivariate Fit of Log(TSS) By log(turbidity).

Table 3. Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.8366546	0.212672	3.93	0.0001
Log(Turbidity)	0.7778152	0.044577	17.45	<.0001

Thus, it appears that the log-linear model best describe the field data presented in Table 1. While both models exhibited no lack of fit the log-linear model have a much better R-Square and hence linear correlation 0.893.

Conclusions.

The field data collected during the sampling years of 2005 and 2006 by the Army Corps of Engineers at Fort Bennng, GA is best summarized by a log-linear model which best describes the relationship between Total Suspended Solids (mg/L) and Turbidity. The least squares model is given below

$$\text{Log(TSS)} = 0.8367 + 0.7778 * \text{Log(Turbidity)}$$

and explains 70.4% of the total variation. It shows no indication of lack of fit and is supported in the literature by several researchers. Mathematically, this is an exponential model of the form

$$Y = \alpha X^{\beta}$$

For this set of data, the model is:

$$TSS = 2.3087 * Turbidity^{0.7778}$$

This relationship adequately predicts concentrations of suspended materials from the more easily measured turbidity measures. Hence, one could then use this predictive model in their assessment of erosion as it relates to the total suspended solids observed in streams on the Fort Benning installation.

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Appendix I: Turbidity and suspended solids data

Table 73. Total Suspended Solids and Turbidity

Creek	Date	Sample	Total SS(mg/L)	Storm Time	Turbidity	Velocity (f/s)	Level(ft)
North Randal	08/22/2006	1	248	8:51 PM	366.70	1.52	0.76
North Randal	08/22/2006	2	346	9:50 PM	540.70	0.76	0.99
North Randal	08/22/2006	3	310	10:50 PM	474.20	0.45	0.86
North Randal	08/22/2006	4	347	11:50 PM	331.40	1.76	0.75
North Randal	08/22/2006	5	200	12:50 AM	290.80	-0.14	0.77
North Randal	08/22/2006	6	183	1:50 AM	255.10	0.07	0.72
North Randal	06/24/2006	1	659	5:39 PM	417.80	-1.06	0.80
North Randal	06/24/2006	2	564	6:39 PM	1274.00	-1.55	0.80
North Randal	06/24/2006	3	290	7:30 PM	249.00	-1.16	0.84
North Randal	06/24/2006	4	166	8:39 PM	155.20	-1.00	0.79
North Randal	06/24/2006	5	117	9:39 PM	213.10	-0.82	0.75
North Randal	06/24/2006	6	229	10:39 PM	1268.00	0.22	0.66
Tiger Creek	06/02/2006	1	824	4:15 PM	1102.00	1.33	0.77
Tiger Creek	06/02/2006	2	759	4:19 PM	1041.50	1.35	0.94
Tiger Creek	06/02/2006	3	823	4:24 PM	965.90	1.38	1.15
Tiger Creek	06/02/2006	4	623	4:29 PM	890.40	1.41	1.36
Tiger Creek	06/02/2006	5	520	4:34 PM	784.40	1.40	1.41
Tiger Creek	06/02/2006	6	399	4:39 PM	670.70	1.37	1.43
Tiger Creek	06/02/2006	7	329	4:44 PM	557.00	1.35	1.45
Tiger Creek	06/02/2006	8	134	4:54 PM	424.30	1.30	1.35
Tiger Creek	06/02/2006	9	176	5:04 PM	315.00	1.23	1.22
Tiger Creek	06/02/2006	10	137	5:14 PM	225.40	1.14	1.07
Tiger Creek	06/02/2006	11	125	5:29 PM	195.90	0.89	0.87
Tiger Creek	05/10/2006	1	1008	5:07 PM	680.60	1.11	0.97
Tiger Creek	05/10/2006	2	516	5:12 PM	852.20	1.43	1.17
Tiger Creek	05/10/2006	3	360	5:17 PM	942.40	1.51	1.43
Tiger Creek	05/10/2006	4	380	5:22 PM	910.40	1.08	1.76
Tiger Creek	05/10/2006	5	649	5:27 PM	878.40	0.65	2.10
Tiger Creek	05/10/2006	6	465	5:32 PM	821.60	0.36	2.32
Tiger Creek	05/10/2006	7	444	5:37 PM	633.40	0.24	2.34
Tiger Creek	05/10/2006	8	418	5:47 PM	547.34	0.19	2.33
Tiger Creek	05/10/2006	9	160	5:57 PM	399.54	0.12	2.16
Tiger Creek	05/10/2006	10	182	6:07 PM	309.70	0.10	2.00
Tiger Creek	05/10/2006	11	193	6:22 PM	233.85	0.10	1.79
Tiger Creek	05/10/2006	12	131	6:37 PM	205.11	0.10	1.69
Tiger Creek	05/10/2006	13	134	6:52 PM	218.61	0.10	1.62
Tiger Creek	05/10/2006	14	171	7:07 PM	260.36	0.10	1.62
Tiger Creek	05/10/2006	15	143	7:37 PM	191.65	0.10	1.76
Tiger Creek	05/10/2006	16	135	8:07 PM	166.70	0.10	1.89
Tiger Creek	05/10/2006	17	231	8:37 PM	498.40	0.10	1.94
Tiger Creek	05/10/2006	18	363	9:07 PM	1096.00	0.10	1.94
Tiger Creek	05/10/2006	19	262	10:07 PM	899.00	-0.16	2.05
Tiger Creek	05/10/2006	20	183	11:07 PM	374.40	0.26	2.34
Tiger Creek	05/11/2006	21	186	1:07 AM	670.20	-0.11	2.39

Creek	Date	Sample	Total SS(mg/L)	Storm Time	Turbidity	Velocity (f/s)	Level(ft)
Tiger Creek	05/11/2007	22	178	3:07 AM	823.90	0.17	1.98
Tiger Creek	05/10/2006	23	150	9:07 AM	385.10	0.17	1.29
Tiger Creek	05/10/2006	24	125	5:07 PM	147.90	0.09	0.97
Tiger Creek	06/02/2006	1	824	4:15 PM	1102.00	1.33	0.77
Tiger Creek	06/02/2006	2	759	4:19 PM	1041.50	1.35	0.94
Tiger Creek	06/02/2006	3	823	4:24 PM	965.90	1.38	1.15
Tiger Creek	06/02/2006	4	623	4:29 PM	890.40	1.41	1.36
Tiger Creek	06/02/2006	5	520	4:34 PM	784.40	1.40	1.41
Tiger Creek	06/02/2006	6	399	4:39 PM	670.70	1.37	1.43
Tiger Creek	06/02/2006	7	329	4:44 PM	557.00	1.35	1.45
Tiger Creek	06/02/2006	8	134	4:54 PM	424.30	1.30	1.35
Tiger Creek	06/02/2006	9	176	5:04 PM	315.00	1.23	1.22
Tiger Creek	06/02/2006	10	137	5:14 PM	225.40	1.14	1.07
Tiger Creek	06/02/2006	11	125	5:29 PM	195.90	0.89	0.87
Pine Knot	05/11/2006	1	30	2:21 AM	65.40	1.14	2.31
Pine Knot	05/11/2006	2	40	2:25 AM	64.50	1.12	2.31
Pine Knot	05/11/2006	3	38	2:30 AM	63.30	1.10	2.32
Pine Knot	05/11/2006	4	43	2:35 AM	63.10	1.08	2.32
Pine Knot	05/11/2006	5	42	2:40 AM	55.60	1.07	2.33
Pine Knot	05/11/2006	6	46	2:45 AM	51.80	1.06	2.33
Pine Knot	05/11/2006	7	44	2:50 AM	51.00	1.08	2.34
Pine Knot	05/11/2006	8	39	3:05 AM	48.40	1.15	2.35
Pine Knot	05/11/2006	9	40	3:20 AM	48.60	1.15	2.37
Pine Knot	05/11/2006	10	46	3:50 AM	52.80	1.15	2.39
Pine Knot	05/11/2006	11	40	4:20 AM	50.20	0.83	2.41
Pine Knot	05/11/2006	12	35	5:20 AM	49.90	1.19	2.44
Pine Knot	05/11/2006	13	7	6:20 AM	68.60	1.18	2.45
Pine Knot	05/11/2006	14	28	7:20 AM	63.80	0.75	2.44
Pine Knot	05/11/2006	15	28	8:20 AM	50.80	1.47	2.44
Pine Knot	05/11/2006	16	29	9:20 AM	45.30	1.01	2.45
Pine Knot	05/11/2006	17	28	10:20 AM	44.80	0.83	2.46
Pine Knot	05/11/2006	18	26	11:20 AM	32.30	0.93	2.49
Pine Knot	05/11/2006	19	18	12:20 PM	27.10	0.99	2.51
Pine Knot	05/11/2006	20	22	2:20 PM	22.00	1.15	2.56
Pine Knot	05/11/2006	21	13	4:20 PM	13.90	1.41	2.61
Pine Knot	05/11/2006	22	14	6:20 PM	15.60	1.25	2.65
Pine Knot	05/11/2006	23	2	10:20 PM	14.30	1.11	2.77
Pine Knot	05/11/2006	24	12	2:20 AM	25.20	0.97	2.91

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14. ABSTRACT

SERDP Ecosystem Management Project (SEMP) was initiated in 1998 by the Strategic Environmental Research and Development Program (SERDP), after a 1997 workshop on Department of Defense ecosystem management challenges. After the workshop, SERDP allocated initial funding to a new project, titled the SERDP Ecosystem Management Project, designated as CS-1114, which changed in mid-2005 to SI-1114. SERDP funded five ecological studies under the guidance of SEMP (SERDP Ecosystem Management Project). Three of the studies focused on identify-ing ecological indicators that reflected training-caused disturbance. Two studies attempted to characterize state-transition thresholds that could be attributed to combined training and land management impacts. This report summarizes the findings and recommendations of these studies with regard to : (1) Potential Application, (2) Disturbance Threshold and Indicators, (3) Stream and Water Quality, and (4) Threatened, Endangered, and At-Risk species.

15. SUBJECT TERMS

Strategic Environmental Research and Development Program (SERDP), environmental planning, land management, ecosystem management, SERDP Ecosystem Management Program (SEMP)

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