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Water Resource Implications of Large-Scale Bioethanol Production in the Southeast

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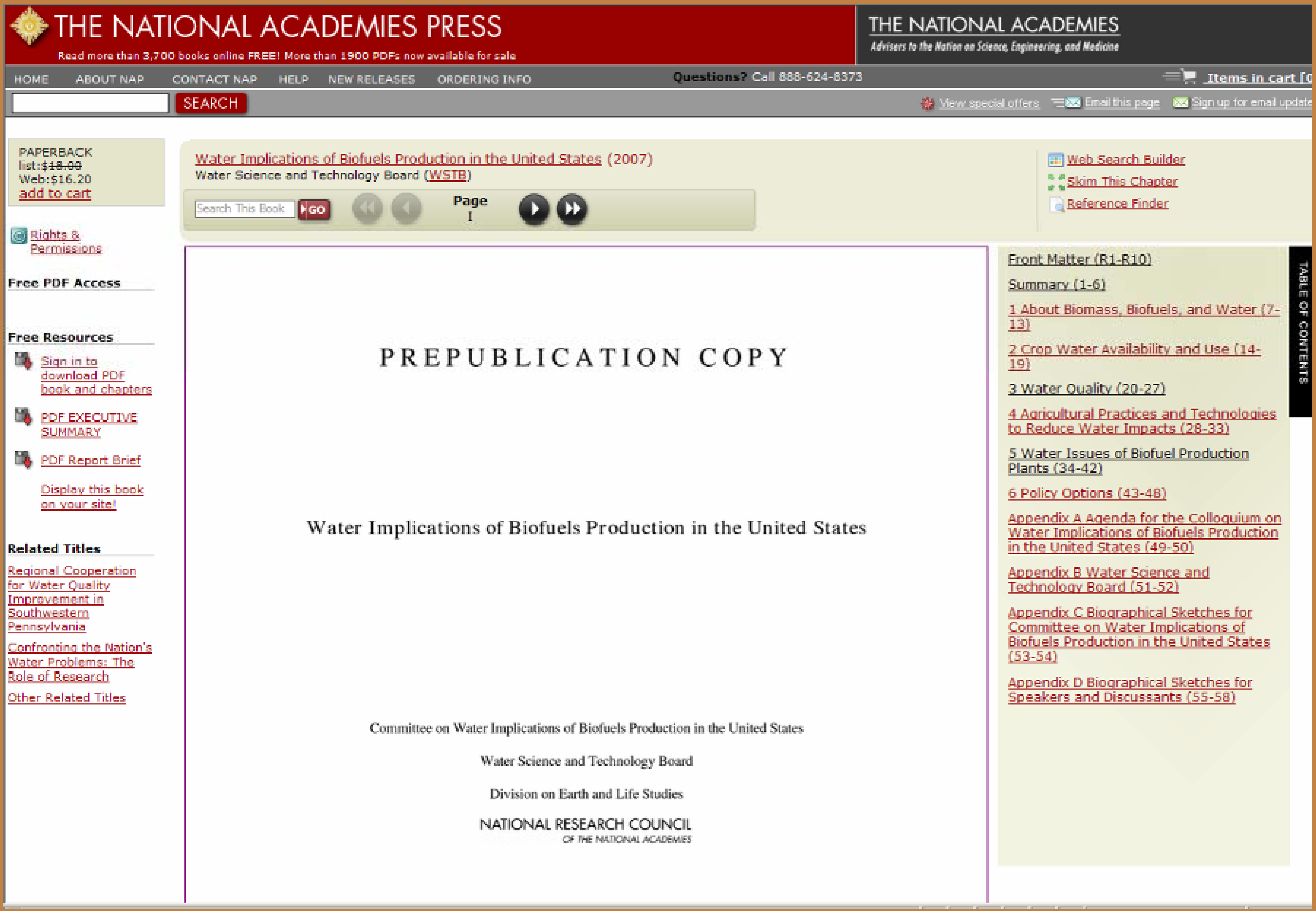

PREPUBLICATION COPY

Water Implications of Biofuels Production in the United States

Committee on Water Implications of Biofuels Production in the United States

Water Science and Technology Board

Division on Earth and Life Studies

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

Front Matter (R1-R10)

Summary (1-6)

1 About Biomass, Biofuels, and Water (7-13)

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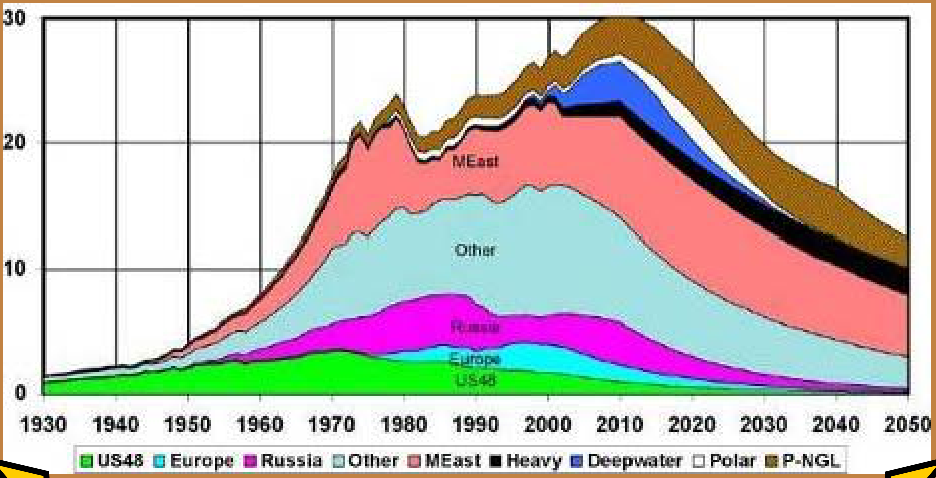
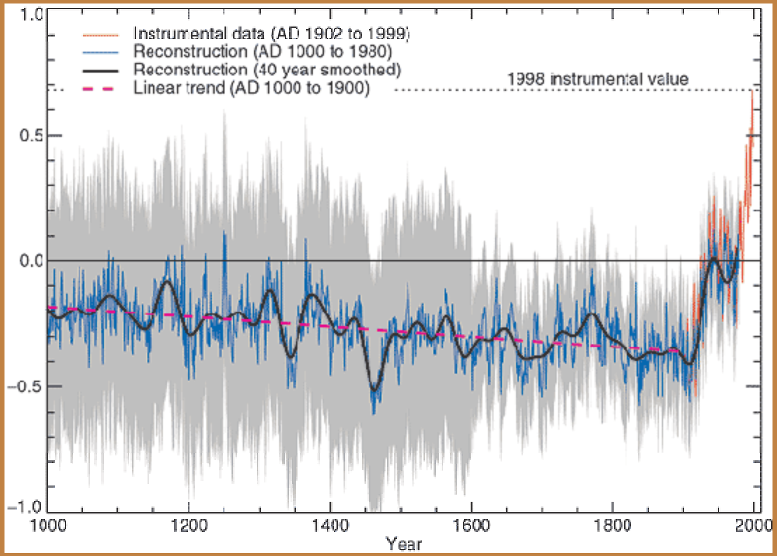
Global Rationale for Alternative Energy



Peak Oil and Price (7/08 = $148.35/bbl)

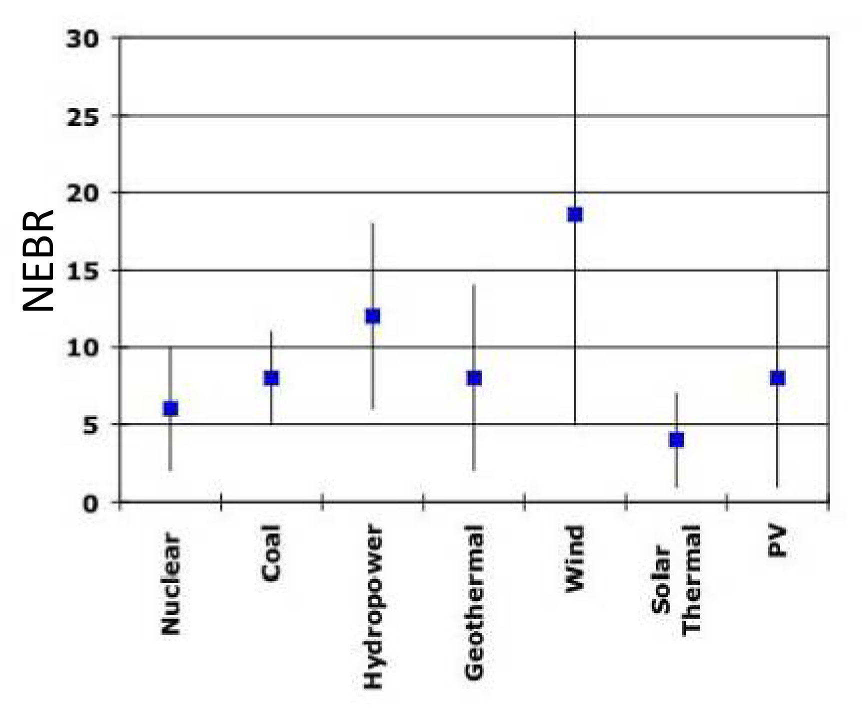


Global Climate Change

Geopolitics

Future Energy Options

- Transportation sector most constrained
  - Liquid fuel (oil) dependence
  - Massive energy req's.
    - 27.5% of total US energy use
    - 2.65E19 J/yr = 26.5 exajoules/yr
- Electricity sector has more alternatives
  - Wind, Coal, Nuclear, Solar
  - NEBR = Energy Delivered/Energy Req'd
- We focus here on <u>liquid fuel</u> replacement
  - Bioethanol/biodiesel

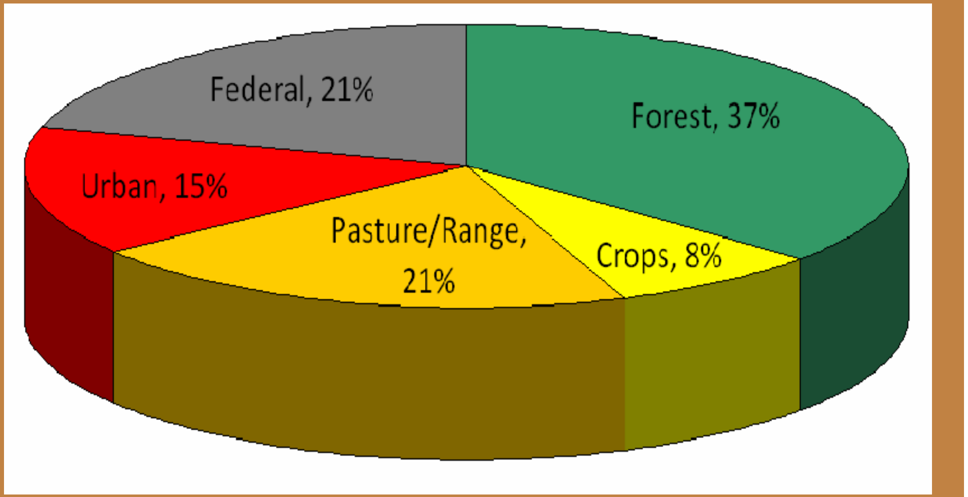


Electric Power Options – Net Energy Benefit Ratio
http://www.eoearth.org/image/EROI_electric_power.jpg

Current Status

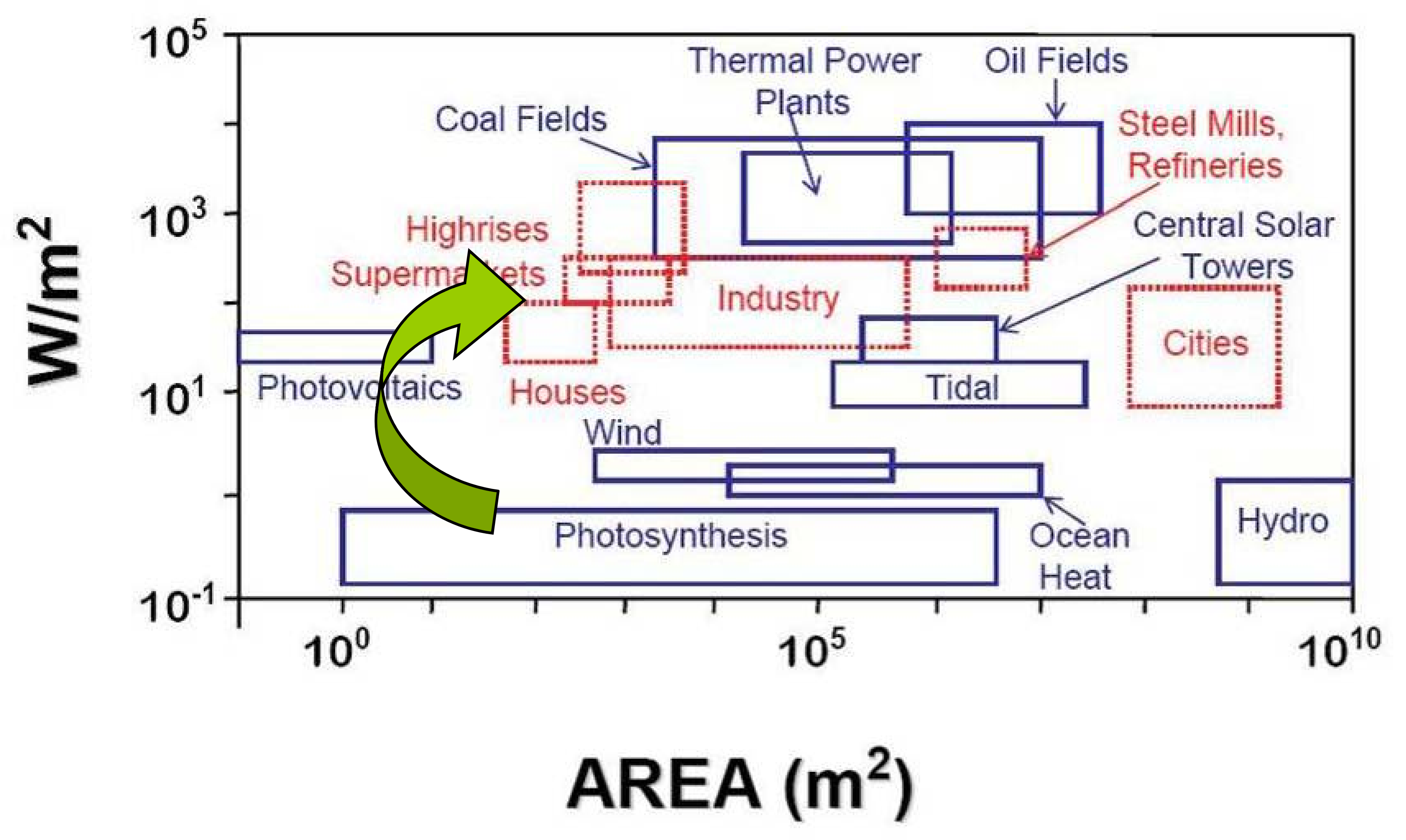
- Current Global Liquid Fuel Consumption
  - 1,200 billion L/yr
  - ~ 3% bioethanol + biodiesel (▲5.3% per yr)
- Principal producers of biofuels
  - USA (corn+) – 24.6 billion L/yr [2007]
    - Current liquid fuel use: 500 billion L/yr
  - Brazil (sugarcane) – 15.1 billion L/yr [2007]
    - Current liquid fuel use: 20 billion L/yr

- Liquid Fuel Consumption in Florida and Georgia
  - Current Use = 1.66E18 GJ/yr
    - (51.5 billion L/yr)
  - Population ~ 27.4 million
  - Land Area ~ 29 million ha
    - Future production constraints?

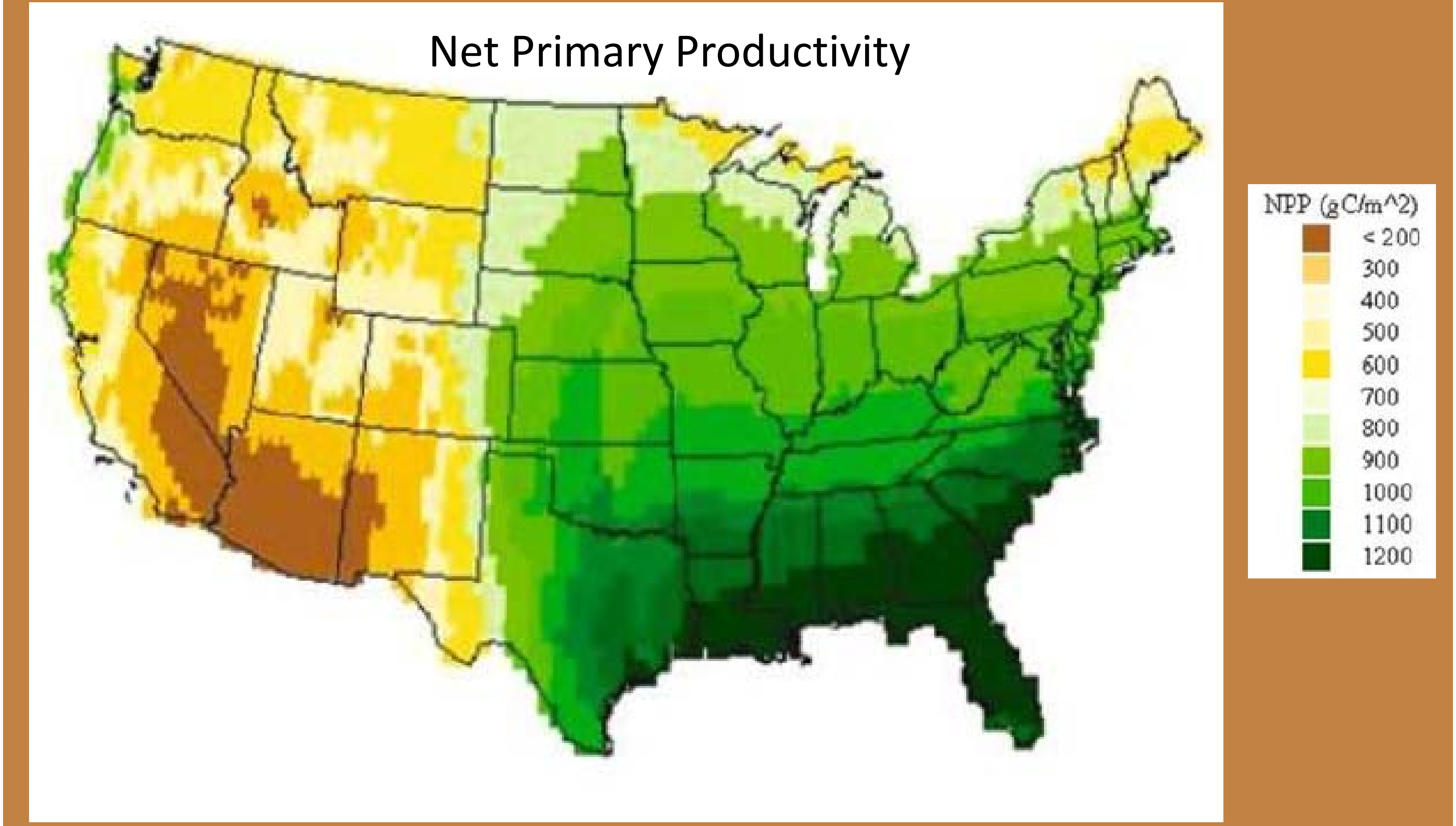


Matching Current and Future Energy Sources to Use

[Power Density for Sources and Uses – Smil 1991]



Where to Grow Future Feedstocks?

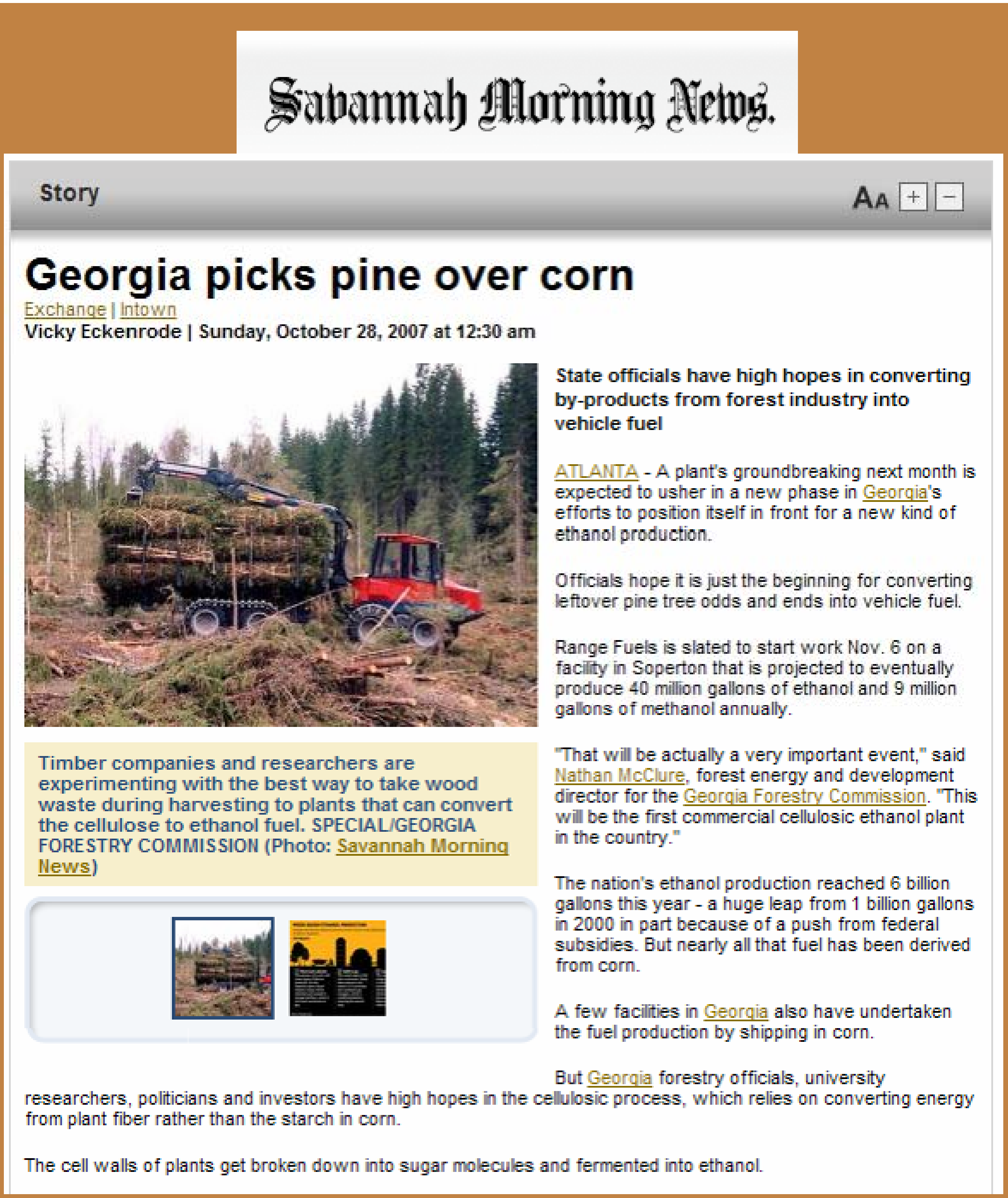

Net Primary Productivity

Izaurralde et al. 2005 (Climatic Change)

What Feedstocks to Grow?

- 95% of US bioethanol is derived from corn
- Brazilian ethanol is principally from sugarcane
- Biodiesel from oil crops (soybeans, sunflowers, algae)
- Cellulosic technology
  - Switchgrass, short-rotation woody crops, “waste”

The Future is Now



Savannah Morning News.

Georgia picks pine over corn

Exchange | Intown

Vicky Eckenrode | Sunday, October 28, 2007 at 12:30 am

Timber companies and researchers are experimenting with the best way to take wood waste during harvesting to plants that can convert the cellulose to ethanol fuel. SPECIAL/GEORGIA FORESTRY COMMISSION (Photo: Savannah Morning News)

State officials have high hopes in converting by-products from forest industry into vehicle fuel

ATLANTA - A plant's groundbreaking next month is expected to usher in a new phase in Georgia's efforts to position itself in front for a new kind of ethanol production.

Officials hope it is just the beginning for converting leftover pine tree odds and ends into vehicle fuel.

Range Fuels is slated to start work Nov. 6 on a facility in Soperton that is projected to eventually produce 40 million gallons of ethanol and 9 million gallons of methanol annually.

"That will be actually a very important event," said Nathan McClure, forest energy and development director for the Georgia Forestry Commission. "This will be the first commercial cellulosic ethanol plant in the country."

The nation's ethanol production reached 6 billion gallons this year - a huge leap from 1 billion gallons in 2000 in part because of a push from federal subsidies. But nearly all that fuel has been derived from corn.

A few facilities in Georgia also have undertaken the fuel production by shipping in corn.

But Georgia forestry officials, university researchers, politicians and investors have high hopes in the cellulosic process, which relies on converting energy from plant fiber rather than the starch in corn.

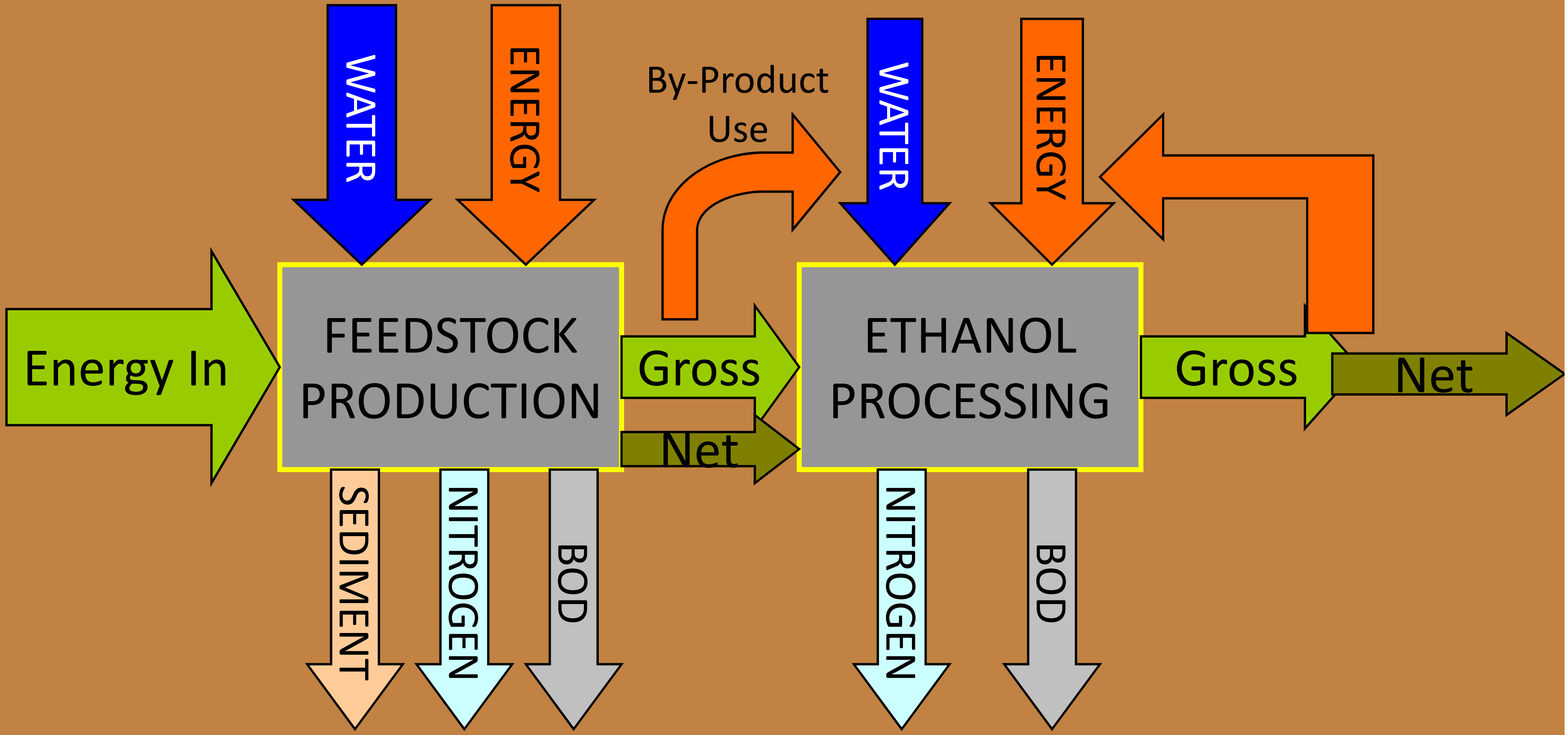
The cell walls of plants get broken down into sugar molecules and fermented into ethanol.

Evaluating Bioethanol Alternatives

- What scientific basis to compare/recommend?
  - Monetary Cost
  - Carbon
  - Geography
  - Net Energy
  - Environmental Cost
    - Water use, Nutrient pollution, Land Requirements
    - BOD loads, Erosion, Wildlife habitat
    - On the basis of Gross vs. Net energy

Evans, J.M. and M.J. Cohen. *In press.* Regional Water Resource Implications of Bioethanol Production in the Southeastern United States. Global Change Biology

Net Energy Concept – Systems Analysis

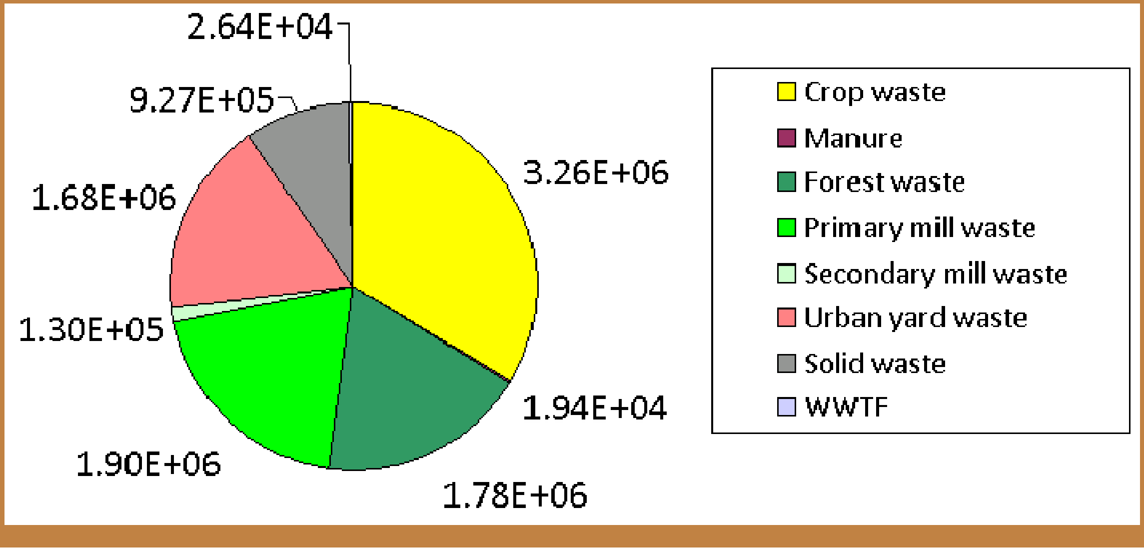


Metrics:

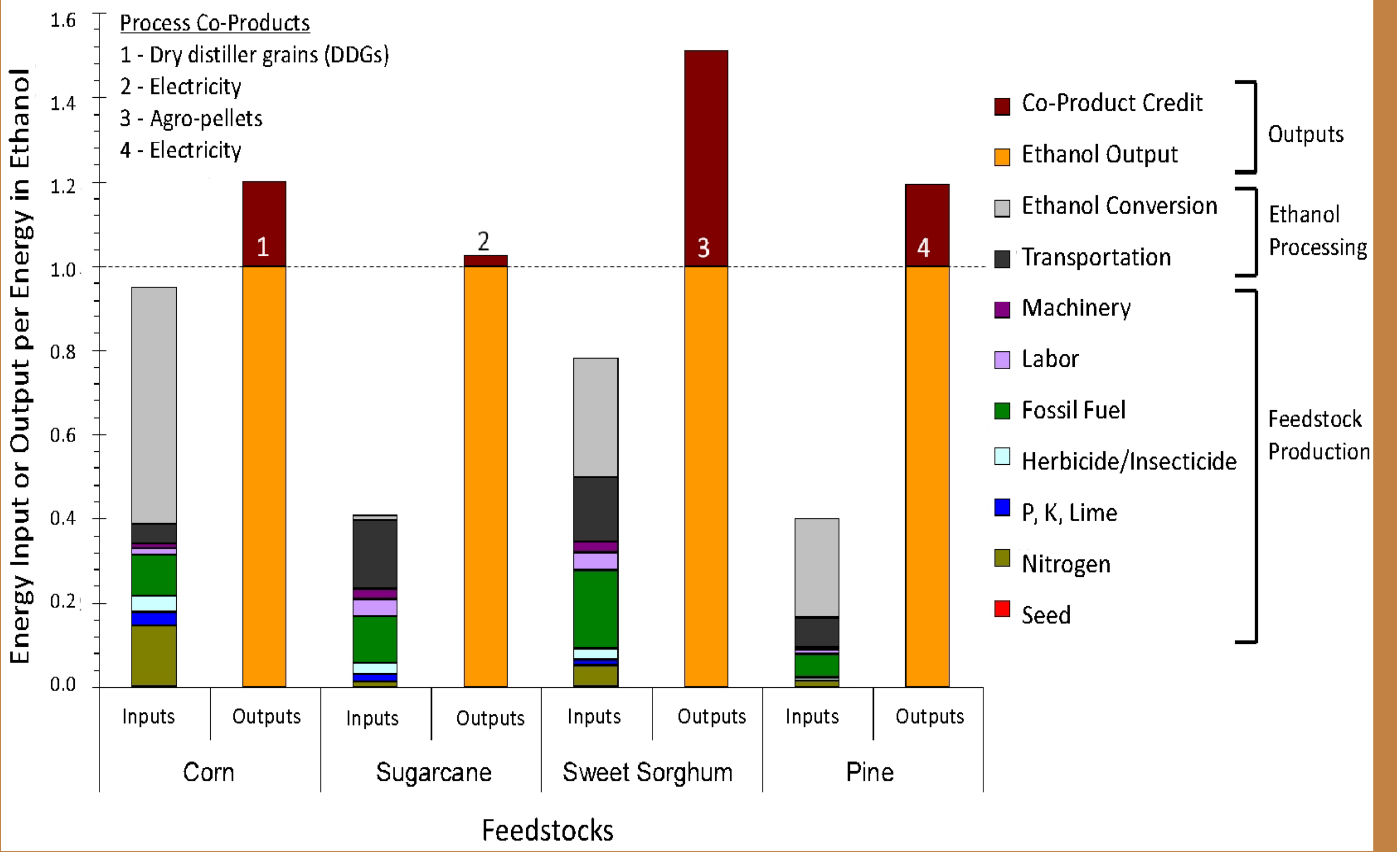
1) Net Energy (GJ_{net} per ha; Energy Return on Energy Invested)
2) Water Use (Mg/GJ_{net})
3) Water Quality (Mg erosion$/GJ_{net}$; $kg\ N/GJ_{net}$; $kg\ BOD/GJ_{net}$)

Waste vs. Dedicated Feedstocks

- Waste biomass (forest harvest residues, citrus peels, municipal solid waste) is bio-energy low hanging fruit
  - High net energy as a by-product (also low environmental cost)
  - Limited in magnitude
- Waste biomass in FL+ GA is 23.7 million tons (NREL 2005)
  - At gross conversion efficiency (300 L EtOH/dry ton) can provide:
    - 9.2% of combined total liquid fuel use
    - 52% of RFS mandates (136 billion L by 2022) assuming production proportional to SE consumption (currently 10% of national use)



Net Energy Balance



Comparative Net Energy Balances

CORN	SUGARCANE	SORGHUM	WOOD
FEEDSTOCK	FEEDSTOCK	FEEDSTOCK	FEEDSTOCK
Yields: 107 GJ/ha/yr	Yield: 164 GJ/ha/yr	Yield: 159 GJ/ha/yr	Yield: 60 GJ/ha/yr
Inputs: 37 GJ/ha/yr	Inputs: 38 GJ/ha/yr	Inputs: 55 GJ/ha/yr	Inputs: 5.7 GJ/ha/yr
–N, Diesel, Pest.	–Diesel, Pest., N	–Diesel, Labor, N	–Diesel, Labor, N
–$\text{NEBR}_{\text{PROD}}$ ~ 2.9:1	–$\text{NEBR}_{\text{PROD}}$ ~ 4.3:1	–$\text{NEBR}_{\text{PROD}}$ ~ 2.9:1	–$\text{NEBR}_{\text{PROD}}$ ~ 10.5:1
PROCESSING	PROCESSING	PROCESSING	PROCESSING
Transport ~ 0.99 MJ/L	Transport ~ 3.47 MJ/L	Transport ~ 3.28 MJ/L	Transport ~ 1.50 MJ/L
Refining ~ 12.00 MJ/L	Refining ~ 0.28 MJ/L	Refining ~ 6.00 MJ/L	Refining ~ 5.00 MJ/L
CO-PRODUCT	CO-PRODUCT	CO-PRODUCT	CO-PRODUCT
DDG ~ 4.31 MJ/L	Electricity ~ 0.59 GJ/L	Ag-pellets ~ 10.9 GJ/L	Electricity ~ 4.11 GJ/L
SYSTEM YIELD	SYSTEM YIELD	SYSTEM YIELD	SYSTEM YIELD
NEBR ~ 1.26:1	NEBR ~ 2.51:1	NEBR ~ 1.94:1	NEBR ~ 2.97:1

Evaluating Environmental Resource Costs

- Water
  - Feedstock production requirements (variable)
  - Biorefining requirements (~ 3.5 L_{H2O}/L_{EtOH})
- Pollutants
  - Erosion/Sediment increases
  - Nitrogen enrichment
  - Oxygen consuming wastes
- Wildlife habitat? Diversity?
- “Footprint” evaluations on net energy basis…
  - $/$GJ_{net}$
  - g N/GJ_{net}
  - g H2O/GJ_{net}
  - Hectares/GJ_{net}

Feedstock Water Use: Blue vs. Green Water

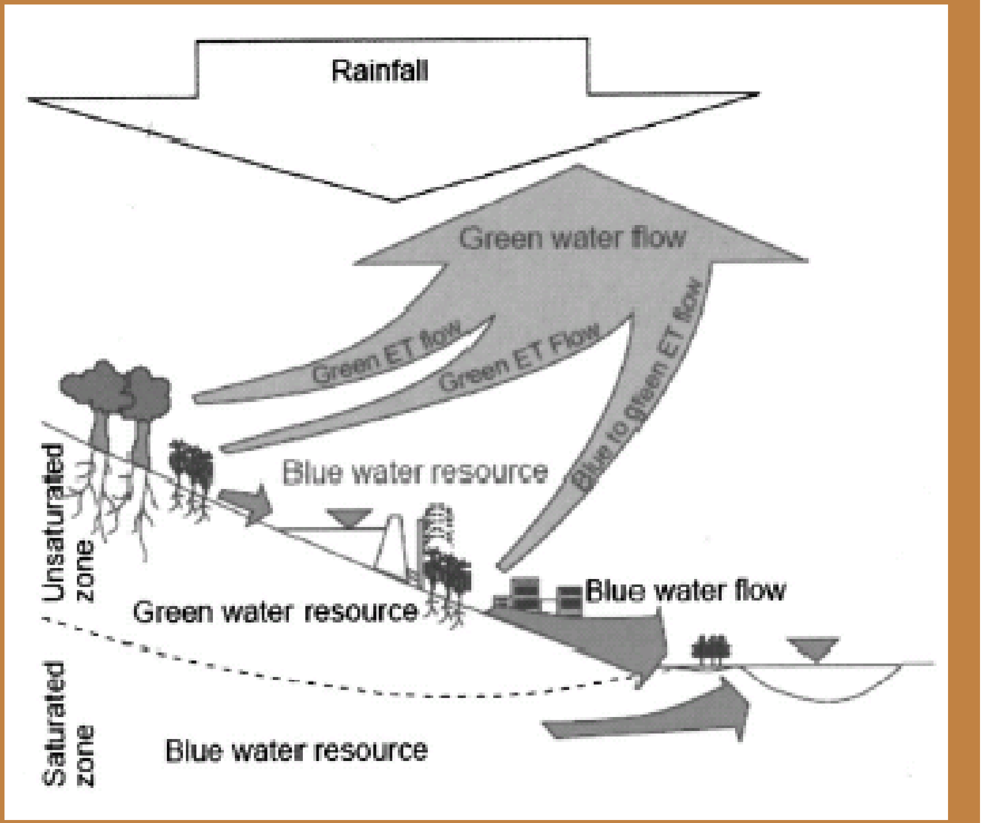
Powell et al. 2005 – Can. J. For. Res.

Runoff/Recharge (Blue Water) = Rainfall – ET

Plantation yields ~ 250 mm less water per year

Green Water = Use

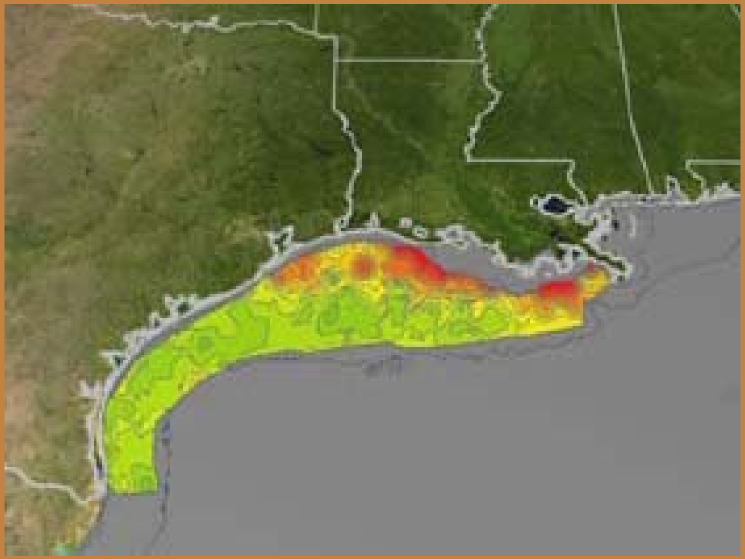
- Corn
  - ET ~ 750 mm over 120 days
    - ET_{ref} ~ 300 mm over 4 months
  - Blue water = 500 mm irrigation
  - Green water = 0 mm
- Sweet Sorghum
  - ET ~ 650 mm over 4 months
    - ET_{ref} ~ 300 mm over 4 months
  - Blue water = 250 mm irrigation
  - Green Water = 100 mm
- Sugarcane
  - ET ~ 1100 mm per year
    - ET_{ref} ~ 750 mm per year
  - Blue water = 725 mm irrigation
  - Green water = 0 mm
- Wood (life cycle)
  - ET ~ 1000 mm per year
    - ET_{ref} ~ 750 mm per year
  - Blue water = 0 (No irrigation)
  - Green water = 250 mm



Falkenmark and Rockstrom 2006
(J Water Resources Planning and Management)

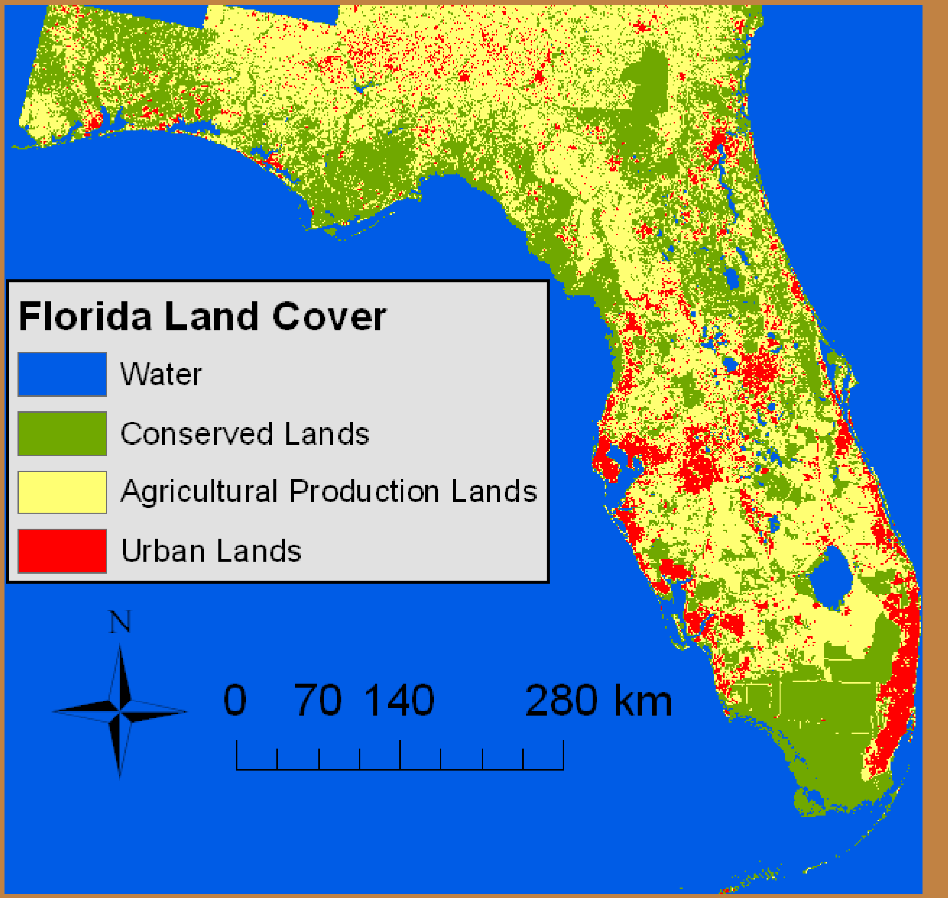
Water Quality Concerns

- Nitrogen pollution
  - Gulf of Mexico hypoxia
  - St. Johns River
- Erosion/sediment production
  - Significant concern in the Piedmont
  - Not evaluated here
- Loads of O_2 consuming wastes
  - BOD ~ 1000 mg/L
  - Low dissolved oxygen is among the most common water quality problems in Florida
  - Not evaluated here

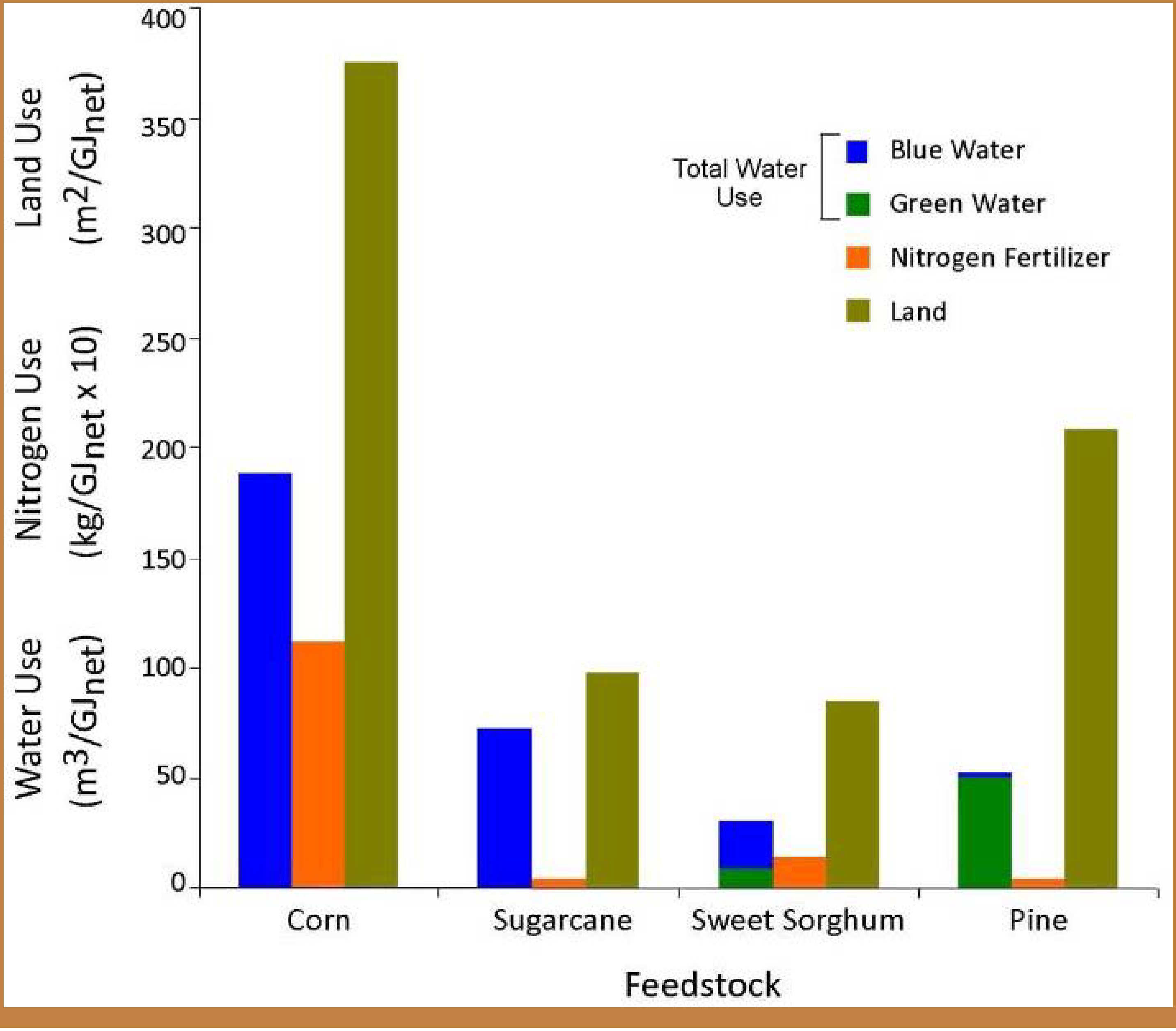


Land Use Concerns

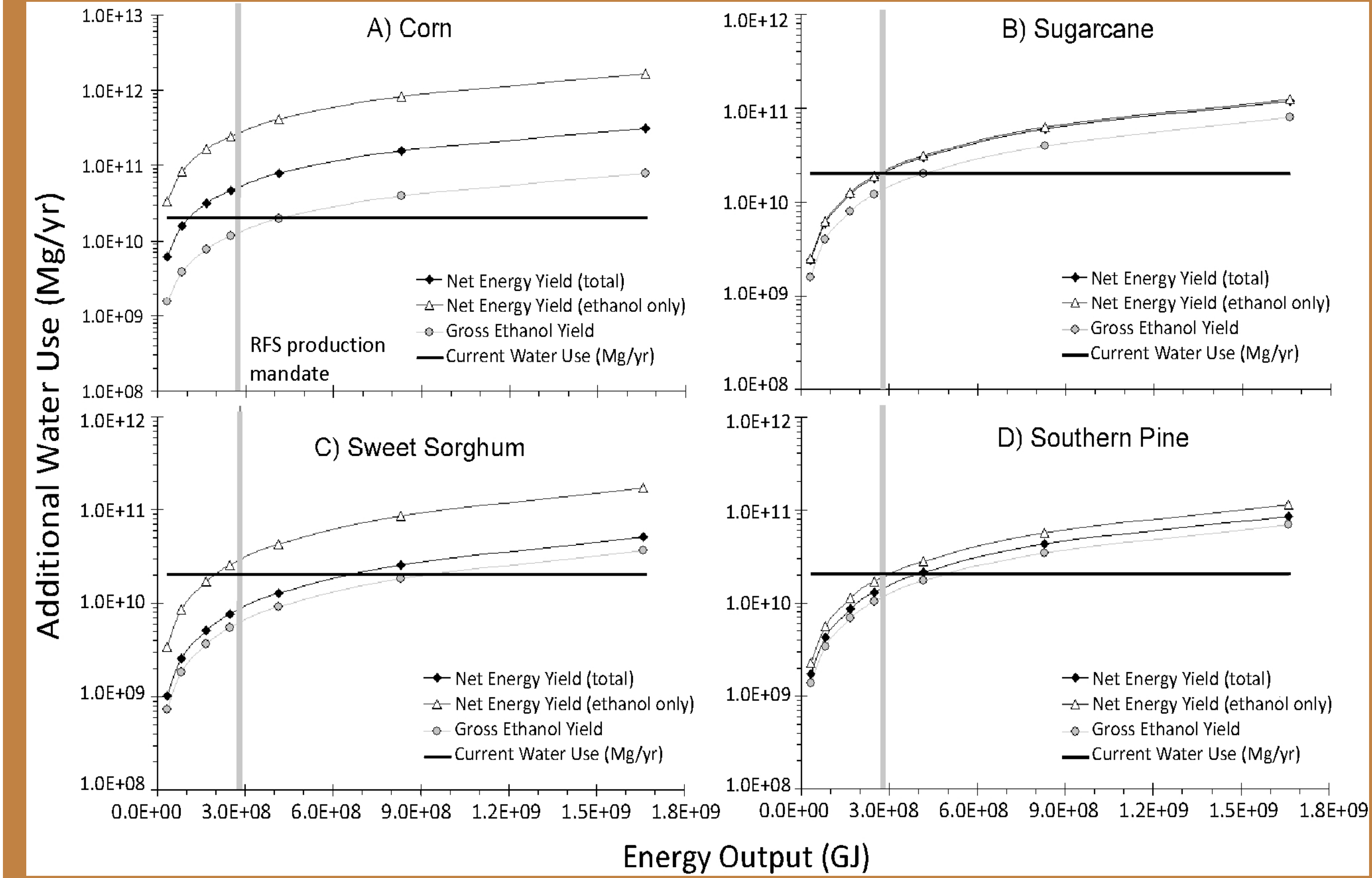
- Current human footprint is large and growing
- Appropriation of land resources for energy production implies “use” trade-offs
- Are conservation lands off limits?



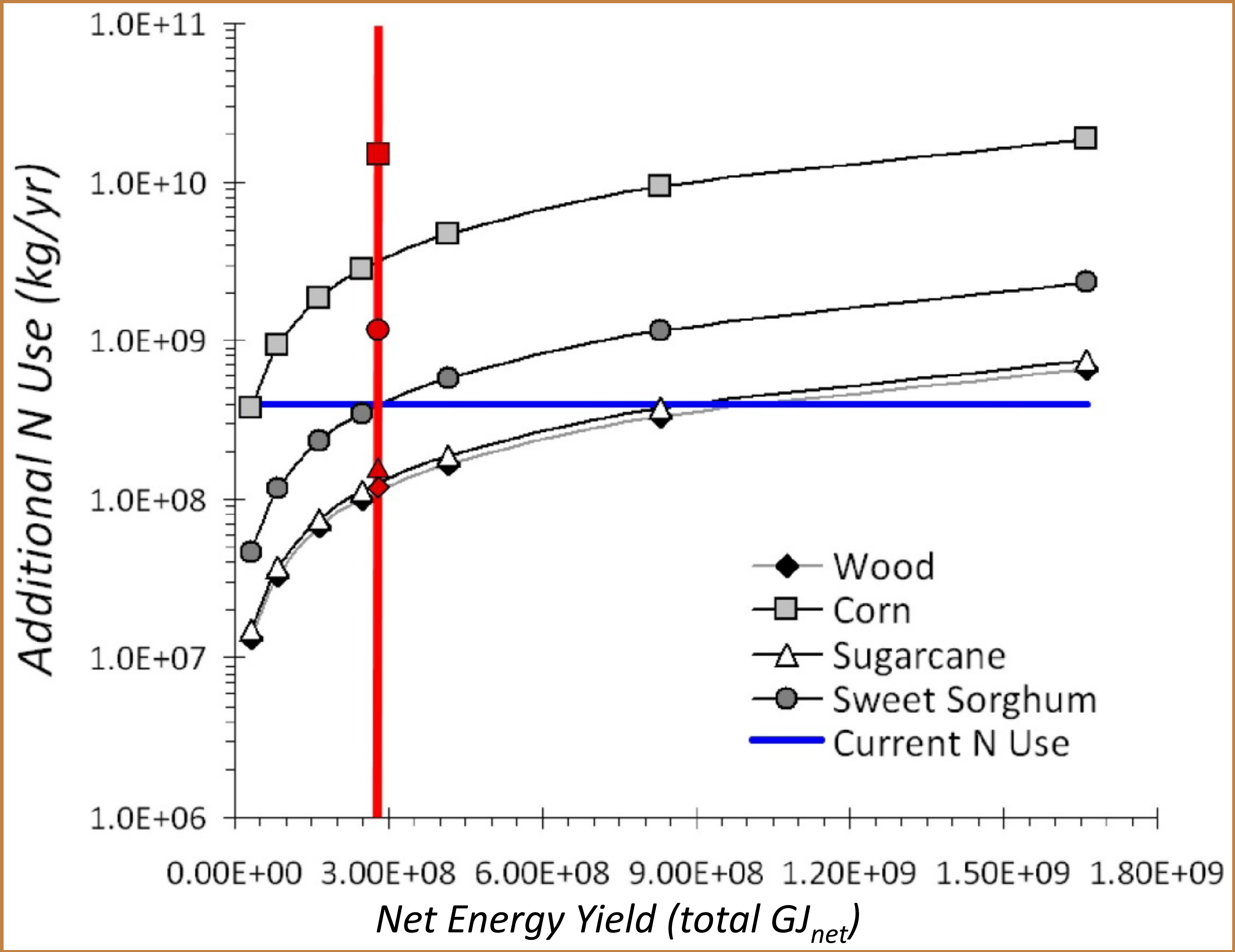
Environmental Resource Use



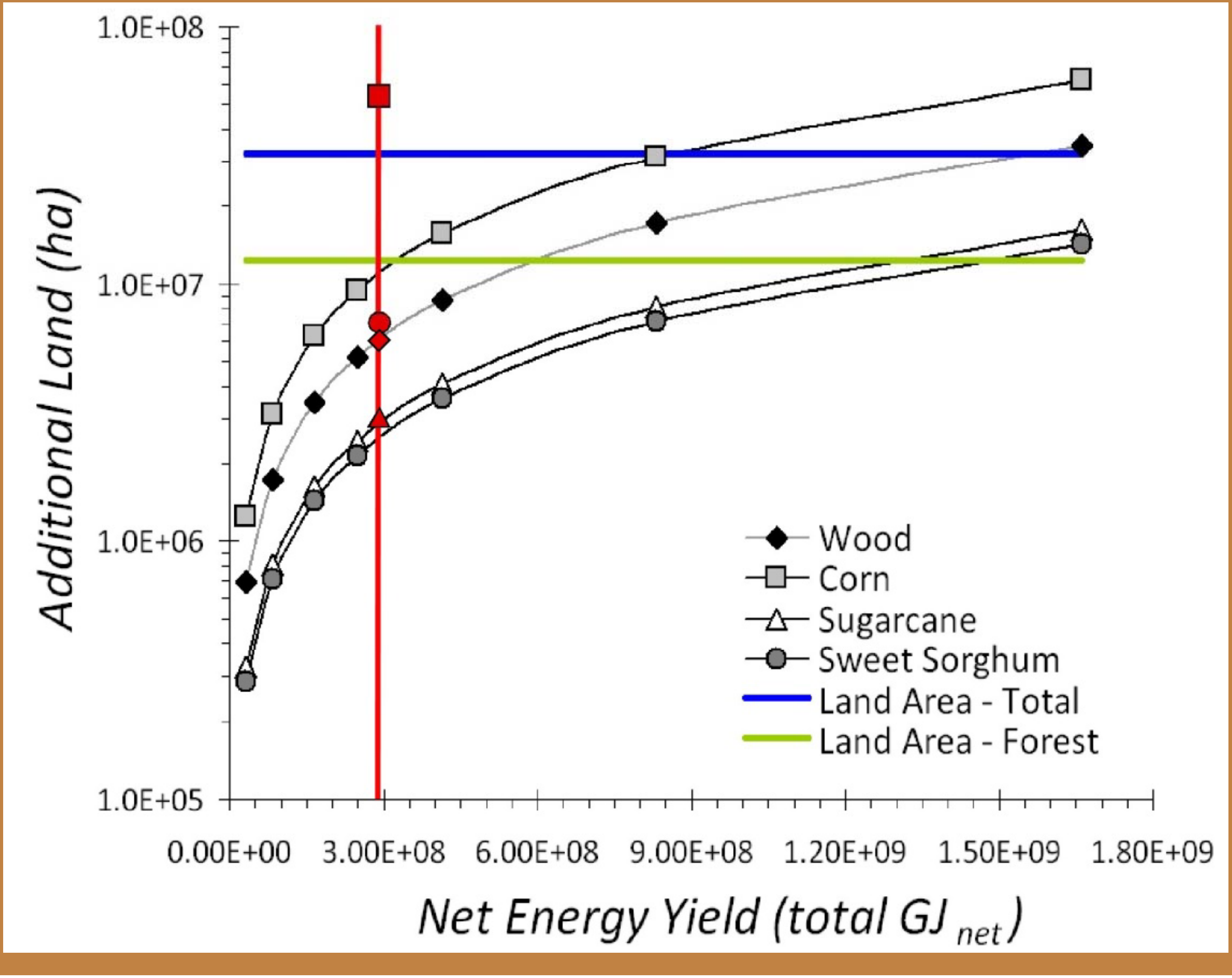
Energy and Water: Gross, Net_{EtOH} and Net_{Total}



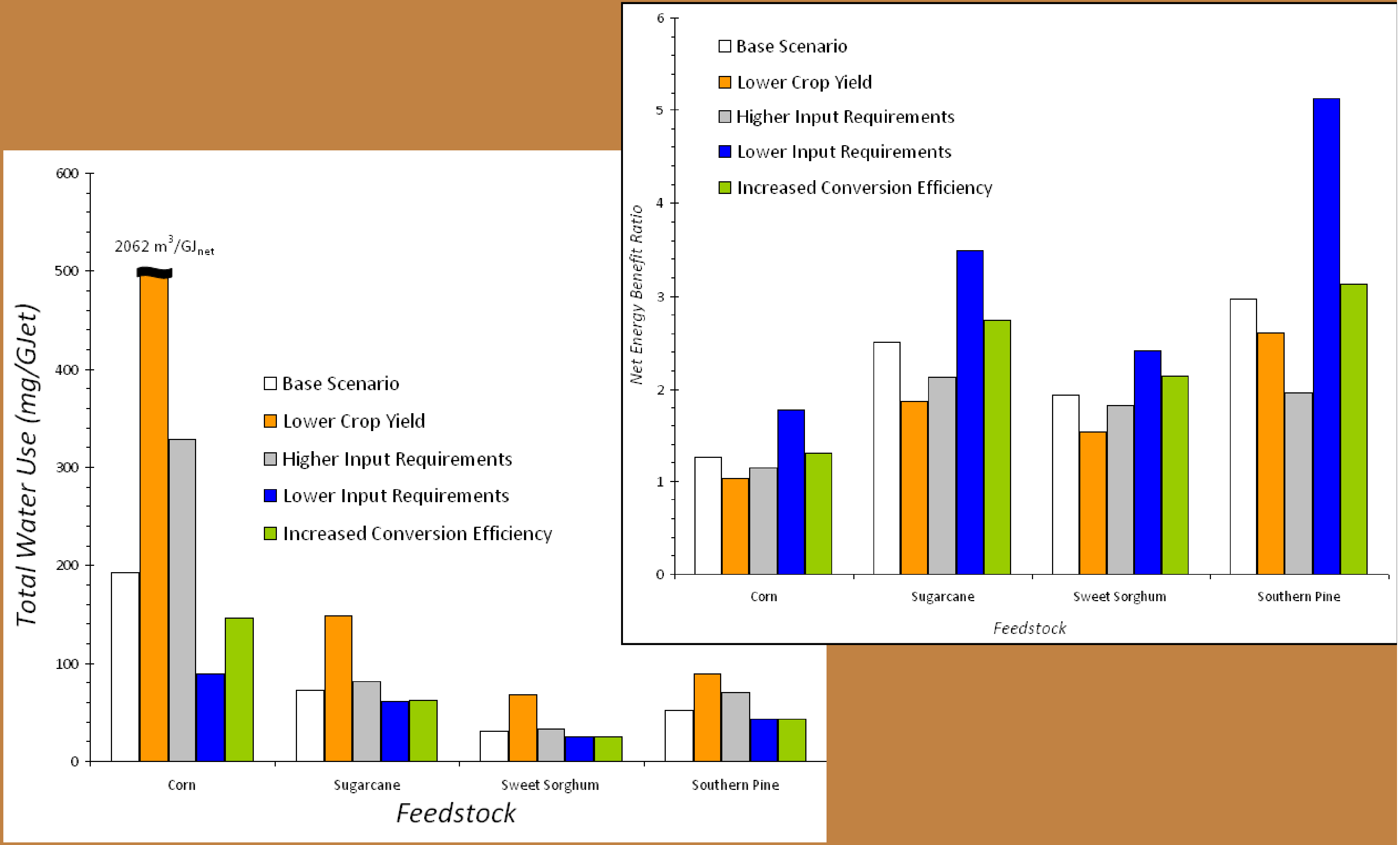
Fuel Replacement Scenarios: Nitrogen



Fuel Replacement Scenarios: Land



Sensitivity Analysis



Summary/Synthesis

- All four SE feedstocks provide net energy
- Southern pine has the highest NEBR (~3:1)
  - Ancillary benefits of forests are also substantially higher
- Hydrologic costs are potentially high and may force competing priorities (e.g., MFLs, TMDLs), particularly when accounting for dispersed water appropriation
  - When using forest feedstocks, double current:
    - Water use at 25% liquid fuel replacement (net)
    - Nitrogen use at 55% liquid fuel replacement
  - Using **all** current forest land at 35% replacement
- Key improvements need to be in conversion efficiency and land use planning

Questions? Comments?

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Acknowledgements: Dr. Angela Lindner, Dr. Mark Brown, Dr. Skip Ingley, Noorie Rajvanshi, Puneet Dwivedi, Tyler Nesbit

L.V. Korhnak

Table 1. Farm energy requirements for southeastern corn production[†]

Item	Application rate, kg/ha	Production energy requirement, MJ/kg[#]	Per hectare energy usage, MJ/ha	Input energy in ethanol production, MJ/liter
Seed[‡]	-	-	280	0.06
Nitrogen[§]	300.00	51.47	15310	3.05
Phosphorus[§]	95.00	9.17	870	0.17
Potash[§]	278.00	5.96	1650	0.33
Lime[§]	189.00	4.61	870	0.17
Herbicide[¶]	6.25	319.00	1990	0.40
Insecticide[¶]	7.25	325.00	2360	0.47
Fossil Fuel[††]	-	-	10250	2.04
Labor[‡‡]	-	-	1800	0.36
Machinery[§§]	-	-	1600	0.32
Total			**36980**	**7.37**

† - *Estimated corn output*: 100,000 kg/ha total fresh weight biomass and 12,600 kg (494 bushels) corn kernels/ha over 120 day growing period (Personal Communication, Brian Scully, USDA, Tifton, GA, September 28, 2007). *Estimated ethanol output* = 5013 l/ha, based on dry mill conversion estimate of 0.398 l/kg corn kernels (Hill *et al.* 2006)

‡ - *Seed per hectare*: Seed energy reported for Midwest (Hill *et al.* 2006) adjusted to account for higher per hectare planting densities in southeast conditions

§ - *N, P, K, and Lime rates*: (Wright *et al.* 2004, Mylavarapu et al. 2007)

¶ - *Herbicide and Insecticide rates*: (Buntin & All 2007)

- *Production life-cycle energy requirements*: (Hill *et al.* 2006)

†† - *Fossil fuels per hectare*: Total fossil fuel consumption for crop planting, harvest, irrigation, farm transportation, and personal commutes estimated at 210 l/ha for Midwest (Hill *et al.* 2006). Our value of 250 l/ha is adjusted higher to account for diesel usage associated with irrigation needs (40 l/ha) in southeast conditions. Life cycle energy cost for liquid fossil fuels estimated at 41 MJ/l.

‡‡ - *Labor per hectare*: Similar to another study (Pimentel and Patzek 2005), we assume 11 hours of labor per hectare calculated at 164 MJ/hr (Pimentel and Patzek 2005). The resultant labor value per bushel of corn harvested (3.61 MJ/bu) is almost equivalent to the custom work energy equivalent (3.56 MJ/bu) reported elsewhere (Shapouri *et al.* 2002).

§§ - *Machinery per hectare*: Machinery energy reported for Midwest (Hill *et al.* 2006) adjusted to account for use of pivot irrigation on 100% of farms and allocation of all machinery energy to corn ethanol, rather than in an assumed rotation with soybean biodiesel.

Table 2: Farm energy requirements for Florida sugarcane production[†]

Item	Application rate, kg/ha	Production energy requirement, MJ/kg	Per hectare energy usage, MJ/ha	Input energy for ethanol production, MJ/liter
Seed[‡]	-	-	-	0.00
Nitrogen[§]	40.00	51.47	2080	0.27
Phosphorus[§]	126.00	9.17	1160	0.15
Potash[§]	186.00	5.96	1110	0.14
Lime[§]	200.00	4.61	920	0.12
Herbicide[¶]	6.00	319.00	1910	0.25
Insecticide[¶]	6.35	325.00	2060	0.27
Fossil Fuel[††]	-	-	18450	2.39
Labor[‡‡]	-	-	6780	0.88
Machinery[§§]	-	-	3840	0.50
Total			**38310**	**4.97**

† - *Estimated sugarcane output*: 94,600 kg/ha per year of fresh weight sugarcane stalks (Alvarez and Polopolus 2002). *Estimated ethanol output*: 7734 l/ha, based on a conversion estimate of 81.75 l/ton sugarcane, which is the average ethanol output from four recent studies (Dias de Oliveira *et al.* 2005, Shapouri and Salassi 2006, Pimentel and Paztek 2005, Macedo *et al.* 2008).

‡ - *Seed per hectare*: Seeds are not utilized for Florida sugarcane production, and thus this input is neglected.

§ - *N and lime rates*: Most Florida sugarcane is grown on organic wetland soils that require no N or lime inputs. Numbers given in this table are based on an estimate that 20% of current crop area requires N inputs (Rice *et al.* 2006). *P and K rates*: (Rice *et al.* 2006)

¶ - *Herbicide rate*: (Rainbolt and Dusky 2007); *Insecticide rate*: (Cherry *et al.* 2001)

- *Production energy requirements*: (Hill *et al.* 2006)

†† - *Fossil fuels per hectare*: Includes diesel and gasoline usage of 320 l/ha for planting, harvest, and farm transport (Salassi and Breaux 2006) and 130 l/ha for water management. Due to pump efficiency improvements, water management diesel usage is assumed to be one half that reported in a previous study (Fluck 1992). Life cycle energy cost for liquid fossil fuels estimated at 41 MJ/l.

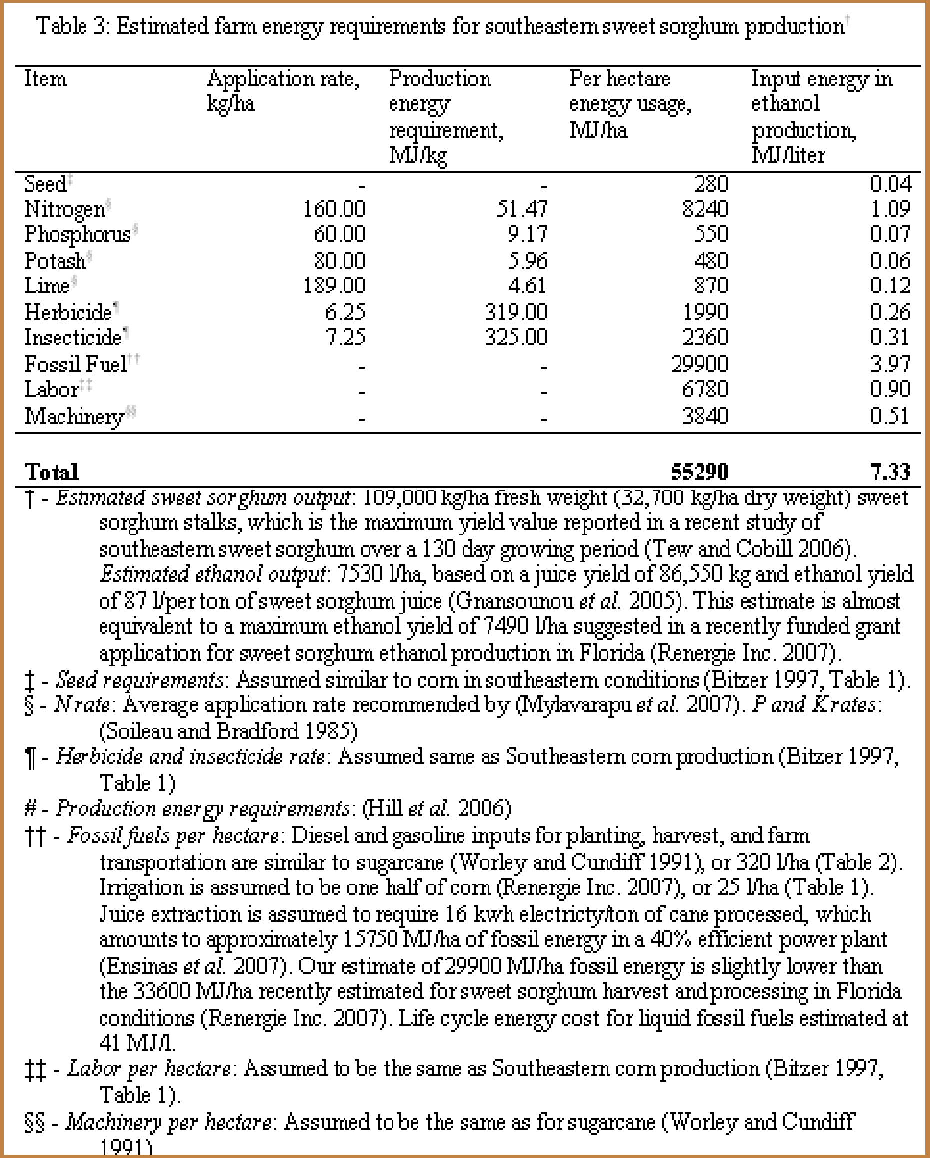

Table 3: Estimated farm energy requirements for southeastern sweet sorghum production[†]

Item	Application rate, kg/ha	Production energy requirement, MJ/kg	Per hectare energy usage, MJ/ha	Input energy in ethanol production, MJ/liter
Seed[‡]	-	-	280	0.04
Nitrogen[§]	160.00	51.47	8240	1.09
Phosphorus[§]	60.00	9.17	550	0.07
Potash[§]	80.00	5.96	480	0.06
Lime[§]	189.00	4.61	870	0.12
Herbicide[¶]	6.25	319.00	1990	0.26
Insecticide[¶]	7.25	325.00	2360	0.31
Fossil Fuel[††]	-	-	29900	3.97
Labor[‡‡]	-	-	6780	0.90
Machinery[§§]	-	-	3840	0.51
Total			**55290**	**7.33**

† - *Estimated sweet sorghum output*: 109,000 kg/ha fresh weight (32,700 kg/ha dry weight) sweet sorghum stalks, which is the maximum yield value reported in a recent study of southeastern sweet sorghum over a 130 day growing period (Tew and Cobill 2006). *Estimated ethanol output*: 7530 l/ha, based on a juice yield of 86,550 kg and ethanol yield of 87 l/per ton of sweet sorghum juice (Gnansounou *et al.* 2005). This estimate is almost equivalent to a maximum ethanol yield of 7490 l/ha suggested in a recently funded grant application for sweet sorghum ethanol production in Florida (Renergie Inc. 2007).

‡ - *Seed requirements*: Assumed similar to corn in southeastern conditions (Bitzer 1997, Table 1).

§ - *N rate*: Average application rate recommended by (Mylavarapu *et al.* 2007). *P and K rates*: (Soileau and Bradford 1985)

¶ - *Herbicide and insecticide rate*: Assumed same as Southeastern corn production (Bitzer 1997, Table 1)

- *Production energy requirements*: (Hill *et al.* 2006)

†† - *Fossil fuels per hectare*: Diesel and gasoline inputs for planting, harvest, and farm transportation are similar to sugarcane (Worley and Cundiff 1991), or 320 l/ha (Table 2). Irrigation is assumed to be one half of corn (Renergie Inc. 2007), or 25 l/ha (Table 1). Juice extraction is assumed to require 16 kwh electricty/ton of cane processed, which amounts to approximately 15750 MJ/ha of fossil energy in a 40% efficient power plant (Ensinas *et al.* 2007). Our estimate of 29900 MJ/ha fossil energy is slightly lower than the 33600 MJ/ha recently estimated for sweet sorghum harvest and processing in Florida conditions (Renergie Inc. 2007). Life cycle energy cost for liquid fossil fuels estimated at 41 MJ/l.

‡‡ - *Labor per hectare*: Assumed to be the same as Southeastern corn production (Bitzer 1997, Table 1).

§§ - *Machinery per hectare*: Assumed to be the same as for sugarcane (Worley and Cundiff 1991).

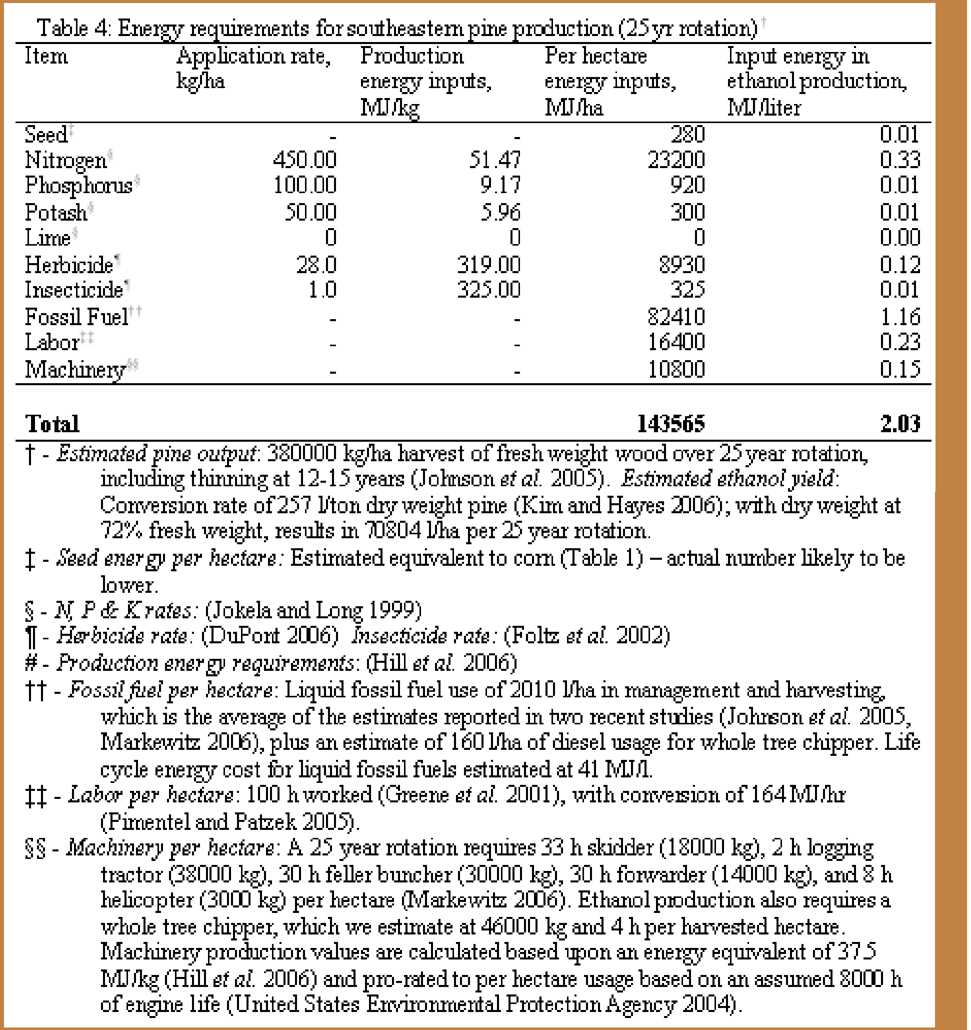

Table 4: Energy requirements for southeastern pine production (25 yr rotation)[†]

Item	Application rate, kg/ha	Production energy inputs, MJ/kg	Per hectare energy inputs, MJ/ha	Input energy in ethanol production, MJ/liter
Seed[‡]	-	-	280	0.01
Nitrogen[§]	450.00	51.47	23200	0.33
Phosphorus[§]	100.00	9.17	920	0.01
Potash[§]	50.00	5.96	300	0.01
Lime[§]	0	0	0	0.00
Herbicide[¶]	28.0	319.00	8930	0.12
Insecticide[¶]	1.0	325.00	325	0.01
Fossil Fuel[††]	-	-	82410	1.16
Labor[‡‡]	-	-	16400	0.23
Machinery[§§]	-	-	10800	0.15
Total			**143565**	**2.03**

† - *Estimated pine output*: 380000 kg/ha harvest of fresh weight wood over 25 year rotation, including thinning at 12-15 years (Johnson *et al.* 2005). *Estimated ethanol yield*: Conversion rate of 257 l/ton dry weight pine (Kim and Hayes 2006); with dry weight at 72% fresh weight, results in 70804 l/ha per 25 year rotation.

‡ - *Seed energy per hectare:* Estimated equivalent to corn (Table 1) – actual number likely to be lower.

§ - *N, P & K rates:* (Jokela and Long 1999)

¶ - *Herbicide rate:* (DuPont 2006) *Insecticide rate:* (Foltz *et al.* 2002)

- *Production energy requirements*: (Hill *et al.* 2006)

†† - *Fossil fuel per hectare:* Liquid fossil fuel use of 2010 l/ha in management and harvesting, which is the average of the estimates reported in two recent studies (Johnson *et al.* 2005, Markewitz 2006), plus an estimate of 160 l/ha of diesel usage for whole tree chipper. Life cycle energy cost for liquid fossil fuels estimated at 41 MJ/l.

‡‡ - *Labor per hectare*: 100 h worked (Greene *et al.* 2001), with conversion of 164 MJ/hr (Pimentel and Patzek 2005).

§§ - *Machinery per hectare:* A 25 year rotation requires 33 h skidder (18000 kg), 2 h logging tractor (38000 kg), 30 h feller buncher (30000 kg), 30 h forwarder (14000 kg), and 8 h helicopter (3000 kg) per hectare (Markewitz 2006). Ethanol production also requires a whole tree chipper, which we estimate at 46000 kg and 4 h per harvested hectare. Machinery production values are calculated based upon an energy equivalent of 37.5 MJ/kg (Hill *et al.* 2006) and pro-rated to per hectare usage based on an assumed 8000 h of engine life (United States Environmental Protection Agency 2004).

Table 5: Energy balances for southeastern ethanol feedstocks (MJ/l)

	Corn	Sugarcane	Sweet sorghum	Pine
Agriculture†	7.37	4.97	7.33	2.03
Transportation‡	0.99	3.47	3.28	1.50
Ethanol conversion§	12.00	0.28	6.00	5.00
Total energy inputs	20.36	8.72	16.61	8.53
Ethanol energy¶	21.26	21.26	21.26	21.26
Net Energy Benefit ratio (MJ/MJ) excluding co-product credit ($\mathrm{NEBR}_{\mathrm{EtOH}}$)	**1.04**	**2.44**	**1.28**	**2.49**
Co-product credit#	4.31	0.59	10.89	4.11
NEB ratio (MJ/MJ) including co-product credit ($\mathrm{NEBR}_{\mathrm{Total}}$)	**1.26**	**2.51**	**1.94**	**2.97**

† - *Agriculture energy*: Tables 1-4

‡ - *Transportation*: An average biomass transport cost of 0.25 MJ/kg and an ethanol transport cost of 0.41 MJ/l, for all feedstocks (Shapouri *et al.* 2002). Ethanol production of 1000 liters from each feedstock requires transport of the following masses: 2513 kg corn kernels (Hill *et al.* 2006); 13000 kg fresh weight sugarcane (Dias de Oliveira *et al.* 2005); 11500 kg sweet sorghum juice (Gnansounou *et al.* 2005, Renergie Inc. 2007); 3890 kg dry weight pine tree chips (Kim and Hayes 2006)

§ - *Ethanol conversion*: Fossil fuel equivalent inputs for dry mill corn ethanol conversion (Hill *et al.* 2006). Fossil fuel equivalent inputs for Brazilian sugarcane ethanol conversion inputs (Dias de Oliveira *et al.* 2005). Sweet sorghum juice conversion assumed to take half the fossil fuel energy inputs of dry mill corn processing (Shapouri and Salassi 2006, Renergie Inc. 2007). Wood conversion for one liter of ethanol using acid pre-hydrolysis and enymatic hydrolysis staged process includes fossil fuel equivalent inputs of 0.35 MJ for 0.08 kg of lime, 4.38 MJ for 0.22 kg of enzymes, 0.26 MJ for 0.005 kg of ammonia, and 0.01 MJ for 0.85 l of natural gas (S&T Consultants Inc. 2006).

¶ - *Ethanol energy*: (Hill *et al.* 2006)

- *Co-product credits*: For corn, co-product value is offset of fossil fuels obtained through production of dried distiller grains with solubles (DDGS) in distilleries (Hill *et al.* 2006). For sugarcane, co-product is offset of natural gas in 40% efficient power plant through export of excess electricity from combustion of bagasse in co-generation plant at distillery (Dias de Oliveira *et al.* 2005). For sweet sorghum, co-product is calculated as an offset of natural gas through combustion of agro-pellets in off-site power plant at an efficiency of 25%. Agro-pellet mass equals 54% of dry weight bagasse, or approximately 8% of fresh weight sweet sorghum (Gnansounou *et al.* 2005), and has an estimated combustion value of 15.07 MJ/kg (Grassi *et al.* 2002). For pine, co-product credit is offset of natural gas in 40% efficient power plant through export of excess electricity from combustion of lignin in distillery (Kim and Hayes 2006).

Table 6: Inputs for southeastern feedstocks per 1000 liters ethanol production. [Inputs per gross GJ ($GJ_{gross\ EtOH}$) of ethanol and gross GJ of ethanol + co-products ($GJ_{gross\ Bioenergy}$) in parentheses.]

	Corn	Sugarcane	Sweet sorghum	Pine
Land area (m^2)†	1995 (94, 78)	1293 (61, 59)	1328 (62, 41)	3530 (166, 139)
Nitrogen (kg)‡	59.3 (2.8, 2.3)	5.2 (0.25, 0.24)	24.4 (1.1, 0.66)	6.4 (0.30, 0.25)
Blue water (m^3)§	1000 (47, 39)	1030 (45, 43)	342 (16, 11)	10 (0.5, 0.4)
Green water (m^3)¶	0 (0, 0)	0 (0)	133 (6, 4)	865 (41, 34)

† - *Land area*: Based upon biomass productivity for each crop (Tables 1-4) and biomass to ethanol and co-product conversion rates (Table 5). Land required for pine forestry is adjusted to an annual basis to produce 1000 liters of ethanol. Although both corn and sweet sorghum are seasonal (120-140 day growth cycle), their land requirement is not annualized. Rather, land required for these crops reflects agricultural land use that must be annually allocated during the peak growing season. The growing cycle for Florida sugarcane is assumed at 1 year.

‡ - *Nitrogen*: Mass amount of N required to produce 1000 liters of ethanol for each crop using values from Tables 1-4. Sugarcane on non-organic soils would result in at least a five-fold increase in N requirement, or 26.5 kg per 1000 liters. Sweet sorghum N fertilization requirement based on N balance estimate is 46 kg per 1000 liters.

§ - *Blue water*: This is defined as the volume of industrial processing water plus irrigation water necessary to produce ethanol feedstock. In terms of industrial processing, corn is assumed to require 3 liters of water per liter of ethanol output, while sugarcane, sweet sorghum, and pine are assumed to require 10 liters of water per liter of ethanol output. Recommended irrigation for southern corn to produce maximum yields is 500 mm (Wright *et al.* 2004). Average irrigation for Florida sugarcane is 725 mm (Marella 2004). Irrigation for sweet sorghum is estimated as one half that of corn (Renergie Inc. 2007), or 250 mm. Pine plantations are assumed to receive no irrigation.

¶ - *Green water*: $GW_{USE} = (ET_{CROP} - ET_{REF} - I) * L_{AREA}$, where ET_{CROP} is average crop evapotranspiration, ET_{REF} is average evapotranspiration of reference ecosystems, I is irrigation applied, and L_{AREA} is land area. ET_{CROP} for corn is 750 mm per 120 day growing cycle (Personal Communication, Brian Scully, USDA, September 27, 2007). ET_{CROP} for sugarcane is 1100 mm per year (Lang *et al.* 2005). ET_{CROP} for sweet sorghum is estimated at 650 mm per 120 day growing cycle (Natural Resources Intitute 2005). ET_{CROP} for southern pine plantation forest averages 1010 mm per year (Gholz and Clark 2002). Upland forests and pastures are assumed as reference ecosystems for corn, sweet sorghum, and pine plantations in Florida and Georgia; these give an average ET_{REF} of 765 mm per year (Sumner and Jacobs 2005, Powell *et al.* 2005). Of this annual ET_{REF}, 300 mm is estimated to occur during the corn and sweet sorghum growing seasons. The Florida Everglades, which has an estimated ET_{REF} of 1000 mm (German 1996), is assumed as the reference ecosystem for sugarcane. Supplemental irrigation of corn and sugarcane completely displaces the estimated difference between ET_{CROP} and ET_{REF}, thereby resulting in no net green water usage.

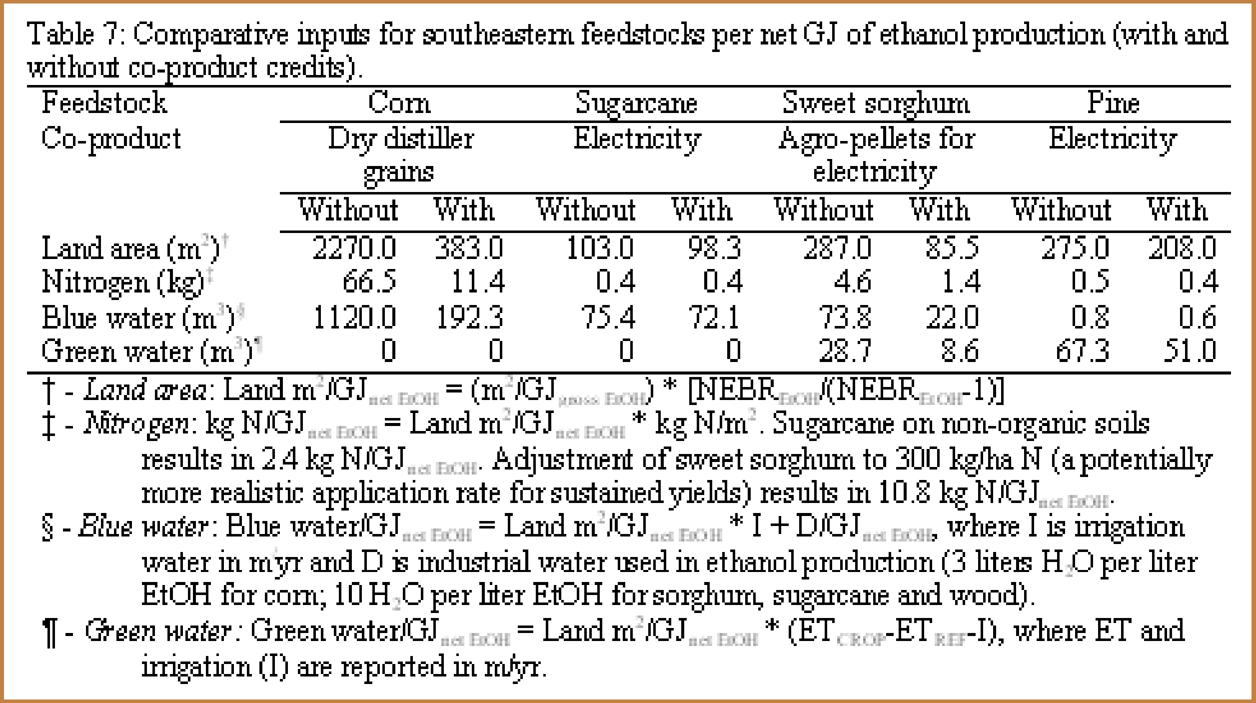

Table 7: Comparative inputs for southeastern feedstocks per net GJ of ethanol production (with and without co-product credits).

Feedstock	Corn		Sugarcane		Sweet sorghum		Pine	
Co-product	Dry distiller grains		Electricity		Agro-pellets for electricity		Electricity	
	Without	With	Without	With	Without	With	Without	With
Land area (m^2)†	2270.0	383.0	103.0	98.3	287.0	85.5	275.0	208.0
Nitrogen (kg)‡	66.5	11.4	0.4	0.4	4.6	1.4	0.5	0.4
Blue water (m^3)§	1120.0	192.3	75.4	72.1	73.8	22.0	0.8	0.6
Green water (m^3)¶	0	0	0	0	28.7	8.6	67.3	51.0

† - *Land area*: Land $m^2/GJ_{net\ EtOH} = (m^2/GJ_{gross\ EtOH}) * [NEBR_{EtOH}/(NEBR_{EtOH}-1)]$

‡ - *Nitrogen*: kg $N/GJ_{net\ EtOH}$ = Land $m^2/GJ_{net\ EtOH}$ * kg N/m^2. Sugarcane on non-organic soils results in 2.4 kg $N/GJ_{net\ EtOH}$. Adjustment of sweet sorghum to 300 kg/ha N (a potentially more realistic application rate for sustained yields) results in 10.8 kg $N/GJ_{net\ EtOH}$.

§ - *Blue water*: Blue water/$GJ_{net\ EtOH}$ = Land $m^2/GJ_{net\ EtOH}$ * I + D/$GJ_{net\ EtOH}$, where I is irrigation water in m/yr and D is industrial water used in ethanol production (3 liters H_2O per liter EtOH for corn; 10 H_2O per liter EtOH for sorghum, sugarcane and wood).

¶ - *Green water*: Green water/$GJ_{net\ EtOH}$ = Land $m^2/GJ_{net\ EtOH}$ * $(ET_{CROP}-ET_{REF}-I)$, where ET and irrigation (I) are reported in m/yr.

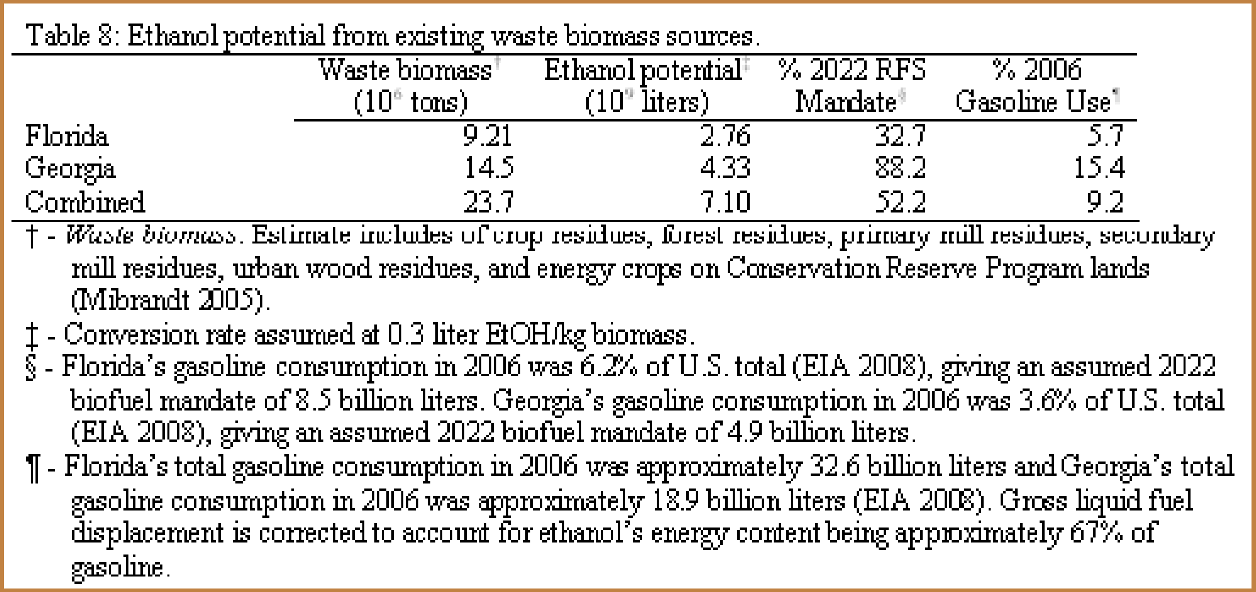

Table 8: Ethanol potential from existing waste biomass sources.

	Waste biomass† (10^6 tons)	Ethanol potential‡ (10^9 liters)	% 2022 RFS Mandate§	% 2006 Gasoline Use¶
Florida	9.21	2.76	32.7	5.7
Georgia	14.5	4.33	88.2	15.4
Combined	23.7	7.10	52.2	9.2

† - *Waste biomass*. Estimate includes of crop residues, forest residues, primary mill residues, secondary mill residues, urban wood residues, and energy crops on Conservation Reserve Program lands (Mibrandt 2005).

‡ - Conversion rate assumed at 0.3 liter EtOH/kg biomass.

§ - Florida's gasoline consumption in 2006 was 6.2% of U.S. total (EIA 2008), giving an assumed 2022 biofuel mandate of 8.5 billion liters. Georgia's gasoline consumption in 2006 was 3.6% of U.S. total (EIA 2008), giving an assumed 2022 biofuel mandate of 4.9 billion liters.

¶ - Florida's total gasoline consumption in 2006 was approximately 32.6 billion liters and Georgia's total gasoline consumption in 2006 was approximately 18.9 billion liters (EIA 2008). Gross liquid fuel displacement is corrected to account for ethanol's energy content being approximately 67% of gasoline.

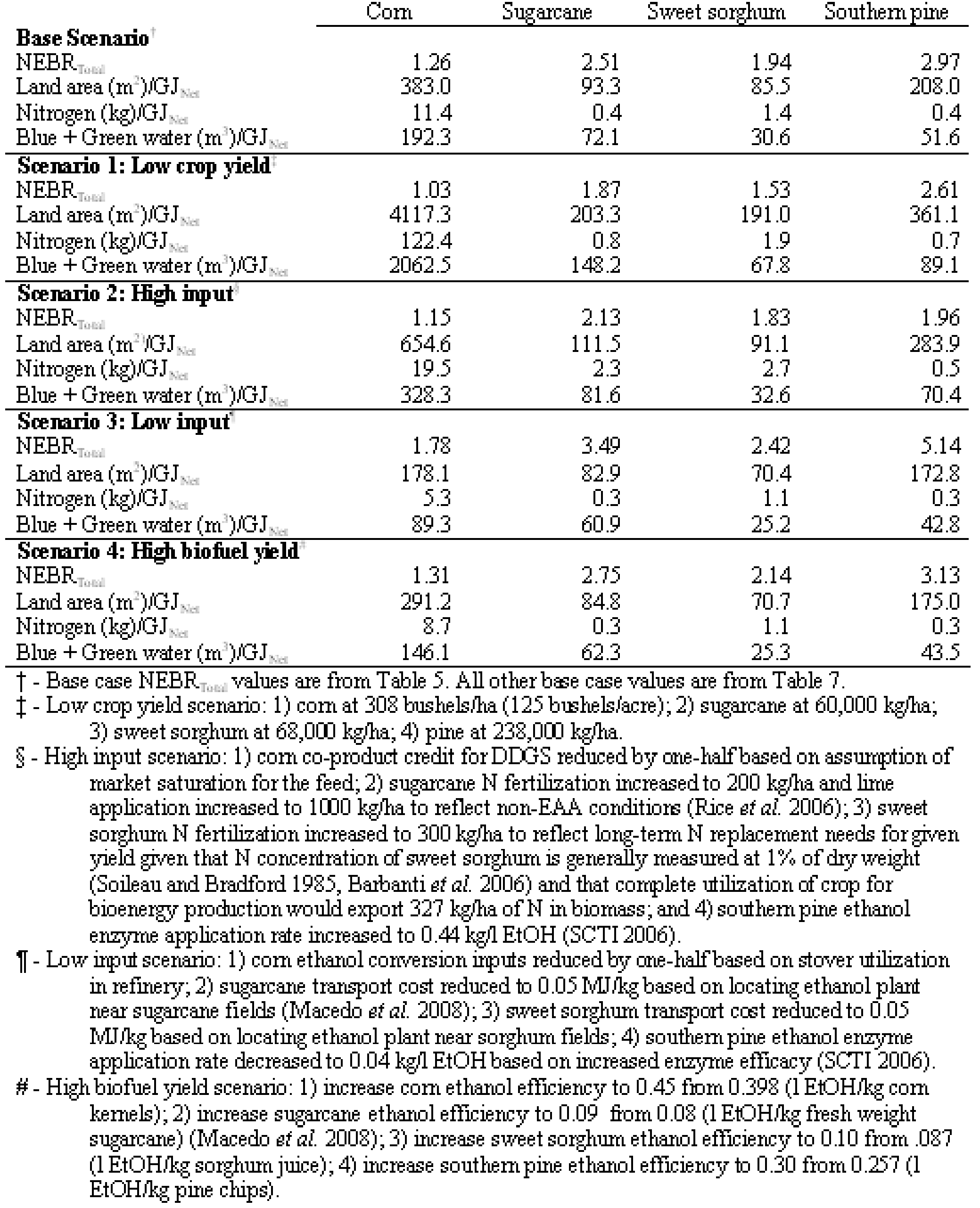

Table 9: Sensitivity analysis of 4 life cycle metrics to key assumptions made for base scenario: feedstock yield (Scenario 1), levels of key inputs (Scenarios 2 and 3), and conversion efficiencies (Scenario 4).

	Corn	Sugarcane	Sweet sorghum	Southern pine
Base Scenario†				
NEBR$_{Total}$	1.26	2.51	1.94	2.97
Land area (m^2)/GJ$_{Net}$	383.0	93.3	85.5	208.0
Nitrogen (kg)/GJ$_{Net}$	11.4	0.4	1.4	0.4
Blue + Green water (m^3)/GJ$_{Net}$	192.3	72.1	30.6	51.6
Scenario 1: Low crop yield‡				
NEBR$_{Total}$	1.03	1.87	1.53	2.61
Land area (m^2)/GJ$_{Net}$	4117.3	203.3	191.0	361.1
Nitrogen (kg)/GJ$_{Net}$	122.4	0.8	1.9	0.7
Blue + Green water (m^3)/GJ$_{Net}$	2062.5	148.2	67.8	89.1
Scenario 2: High input§				
NEBR$_{Total}$	1.15	2.13	1.83	1.96
Land area (m^2)/GJ$_{Net}$	654.6	111.5	91.1	283.9
Nitrogen (kg)/GJ$_{Net}$	19.5	2.3	2.7	0.5
Blue + Green water (m^3)/GJ$_{Net}$	328.3	81.6	32.6	70.4
Scenario 3: Low input¶				
NEBR$_{Total}$	1.78	3.49	2.42	5.14
Land area (m^2)/GJ$_{Net}$	178.1	82.9	70.4	172.8
Nitrogen (kg)/GJ$_{Net}$	5.3	0.3	1.1	0.3
Blue + Green water (m^3)/GJ$_{Net}$	89.3	60.9	25.2	42.8
Scenario 4: High biofuel yield#				
NEBR$_{Total}$	1.31	2.75	2.14	3.13
Land area (m^2)/GJ$_{Net}$	291.2	84.8	70.7	175.0
Nitrogen (kg)/GJ$_{Net}$	8.7	0.3	1.1	0.3
Blue + Green water (m^3)/GJ$_{Net}$	146.1	62.3	25.3	43.5

† - Base case NEBR$_{Total}$ values are from Table 5. All other base case values are from Table 7.

‡ - Low crop yield scenario: 1) corn at 308 bushels/ha (125 bushels/acre); 2) sugarcane at 60,000 kg/ha; 3) sweet sorghum at 68,000 kg/ha; 4) pine at 238,000 kg/ha.

§ - High input scenario: 1) corn co-product credit for DDGS reduced by one-half based on assumption of market saturation for the feed; 2) sugarcane N fertilization increased to 200 kg/ha and lime application increased to 1000 kg/ha to reflect non-EAA conditions (Rice *et al.* 2006); 3) sweet sorghum N fertilization increased to 300 kg/ha to reflect long-term N replacement needs for given yield given that N concentration of sweet sorghum is generally measured at 1% of dry weight (Soileau and Bradford 1985, Barbanti *et al.* 2006) and that complete utilization of crop for bioenergy production would export 327 kg/ha of N in biomass; and 4) southern pine ethanol enzyme application rate increased to 0.44 kg/l EtOH (SCTI 2006).

¶ - Low input scenario: 1) corn ethanol conversion inputs reduced by one-half based on stover utilization in refinery; 2) sugarcane transport cost reduced to 0.05 MJ/kg based on locating ethanol plant near sugarcane fields (Macedo *et al.* 2008); 3) sweet sorghum transport cost reduced to 0.05 MJ/kg based on locating ethanol plant near sorghum fields; 4) southern pine ethanol enzyme application rate decreased to 0.04 kg/l EtOH based on increased enzyme efficacy (SCTI 2006).

- High biofuel yield scenario: 1) increase corn ethanol efficiency to 0.45 from 0.398 (l EtOH/kg corn kernels); 2) increase sugarcane ethanol efficiency to 0.09 from 0.08 (l EtOH/kg fresh weight sugarcane) (Macedo *et al.* 2008); 3) increase sweet sorghum ethanol efficiency to 0.10 from .087 (l EtOH/kg sorghum juice); 4) increase southern pine ethanol efficiency to 0.30 from 0.257 (l EtOH/kg pine chips).