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**Regional Water Resource Implications of Bioethanol Production in the Southeastern
United States**

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1 **Abstract**

2 The Energy Independence and Security Act of 2007 mandates U.S. production of 136 billion
3 liters of biofuel by 2022. This target implies an appropriation of regional primary production for
4 dedicated feedstocks at scales that may dramatically affect water supply, exacerbate existing
5 water quality challenges, and force undesirable environmental resource trade-offs. Using a
6 comparative life cycle approach, we assess energy balances and water resource implications for
7 four dedicated ethanol feedstocks – corn, sugarcane, sweet sorghum, and southern pine – in two
8 southeastern states, Florida and Georgia, which are a presumed epicenter for future biofuel
9 production. Net energy benefit ratios for ethanol and co-products range were 1.26 for corn, 1.94
10 for sweet sorghum, 2.51 for sugarcane, and 2.97 for southern pine. Corn also has high nitrogen
11 (N) and water demand (11.2 kg and 188 m³ per GJ_{net}, respectively) compared to other feedstocks,
12 making it a poor choice for regional ethanol production. Southern pine, in contrast, has relatively
13 low N demand (0.4 kg/GJ_{net}) and negligible irrigation needs. However, it has comparatively low
14 gross productivity, which results in large land area per unit ethanol production (208 m²/GJ_{net}),
15 and, by association, substantial indirect and incremental water use (51 m³/GJ_{net}). Ultimately, all
16 four feedstocks require substantial land (10.1, 3.1, 2.5 and 6.1 million ha for corn, sugarcane,
17 sweet sorghum and pine, respectively), annual nitrogen fertilization (3230, 574, 396, 109 million
18 kg N) and annual total water (54,400, 20,840, 8,840 and 14,970 million m³) resources when
19 scaled up to meet EISA renewable fuel standards (RFS) production goals. This production
20 would, in turn, offset only 17.5% of regional gasoline consumption on a gross basis, and
21 substantially less when evaluated on a net basis. Utilization of existing waste biomass sources
22 may ameliorate these effects, but does not obviate the need for dedicated primary feedstock
23 production. Careful scrutiny of environmental trade-offs is necessary before embracing
24 aggressive ethanol production mandates.

25 **Keywords:** life-cycle analysis, nitrogen pollution, land use change, net energy, environmental
26 impacts, bioenergy

1 **Introduction**

2 Interrelated concerns about increasing oil prices, national security, and global climate
3 change are driving large-scale efforts to implement sustainable energy alternatives. Biofuels are
4 widely viewed as a leading alternative to fossil energy, and in recent years favorable government
5 policies have promoted rapid increases in U.S. biofuel production, particularly corn ethanol.
6 Such growth trends are forecast to continue, as Renewable Fuels Standards (RFS) in the Energy
7 Independence and Security Act (EISA) of 2007 mandate the production of 136 billion liters of
8 biofuel, including 83 billion liters derived from non-corn feedstocks, by 2022 (Sissine 2007).
9 This goal amounts to well over 5 times the 24.6 billion liters of ethanol produced in 2007.

10 As biofuel production targets have grown, concerns about social and environmental
11 consequences of large-scale production have also become increasingly prominent. Although
12 most recent life cycle analyses show a positive net energy benefit (NEB) from U.S. corn ethanol
13 and other commercialized biofuel processes when all fossil fuel inputs are taken into account
14 (Shapouri *et al.* 2002, Dias de Oliveira 2005, Hill *et al.* 2006, Schmer *et al.* 2008), significant
15 concerns have been raised by studies that report negative NEBs from U.S. corn ethanol and
16 major cellulosic feedstock alternatives (Giampietro and Ulgiati 2005, Pimentel and Patzek 2005,
17 Pimentel and Patzek 2007). Further, the stated environmental benefits of biofuels have been
18 questioned by studies indicating that land use changes necessary for large-scale feedstock
19 cultivation may exacerbate soil erosion, forest loss, and greenhouse gas emissions at globally
20 significant levels (Giampietro and Ulgiati 2005, Fargione *et al.* 2008, Searchinger *et al.* 2008).
21 Increasing competition between food and fuel markets has also become an economic and
22 geopolitical concern, particularly in light of global food cost inflation, local grain shortages, and
23 food riots observed in 2008. Such criticisms have prompted calls for implementation of biofuel
24 feedstocks that are decoupled from food production and that minimize environmental impacts on

1 a life cycle basis (Hill *et al.* 2006, Schmer *et al.* 2008, Perlack 2005, Tilman *et al.* 2006, Kim and
2 Hayes 2006).

3 Although the water resource implications of biofuel production are less well-studied than
4 other environmental factors, recent reports warn that large-scale production may pose significant
5 threats to both water supply and water quality (Giampietro *et al.* 1997, NRC 2007). A primary
6 concern is that irrigation demands for feedstock production will promote unsustainable
7 exploitation of surface and ground water, resulting in aquatic ecosystem degradation and reduced
8 future agricultural potential (NRC 2007). Several studies have noted likely increases in nutrient,
9 sediment and agrichemical loads to lakes, rivers, estuaries, and near shore waters with
10 accelerated feedstock production (Hill *et al.* 2006, Pimentel and Patzek 2005, NRC 2007); recent
11 growth in Gulf of Mexico hypoxic zone due to increased nitrogen (N) loading that accompanied
12 ethanol-driven increases in corn production area in the U.S. Midwest underscore these concerns
13 (Donner and Kucharik 2008). Given the agricultural extensification that can reasonably be
14 expected to ensue from ethanol production, water resource impacts must be considered alongside
15 established metrics (e.g., energy and carbon balances) in evaluating biofuel policies. Moreover,
16 existing state and federal mandates to maintain minimum water flows and levels, and to restore
17 degraded water quality (Florida Statutes 2008, Code of Federal Regulations 2008) underscore the
18 need for life cycle analyses of biofuels to ensure that policies and incentive structures for biofuel
19 production consider broader environmental protection goals.

20 In this study we compare energy balances and water resource impacts for four potential
21 ethanol feedstocks – corn, sugarcane, sweet sorghum, and southern pine (i.e., plantations of
22 *Pinus elliottii*, slash pine or *Pinus taeda*, loblolly pine) – for two southeastern states, Florida and
23 Georgia. Although neither state is currently a major biofuel producer, both have warm, wet
24 climates that support high primary productivity. Many analysts therefore forecast a rapid

1 expansion of biofuel production in these and other southeastern states as national production
2 mandates take effect (Kim and Hayes 2006), and several new ethanol production facilities that
3 use one or more of the feedstocks we analyze are currently under consideration or active
4 construction in these states. Additional attention has also been paid to ethanol derived from
5 perennial grasses (e.g., switchgrass), but insufficient data were available for compiling a life-
6 cycle analysis for such crops in the southeast region.

7 Like other recent studies, we calculate the net energy benefit ratio (NEBR) for ethanol
8 and co-product energy outputs using a life cycle approach that accounts for all process inputs on
9 a fossil fuel basis. Optimal biomass yields per area and demonstrated ethanol conversion
10 efficiencies are used, providing generous estimates of biofuel yield potential. We extend the
11 analysis to evaluate water resource impacts for feedstocks using four metrics: 1) increased
12 irrigation and industrial withdrawals (i.e., blue water) associated with feedstock and ethanol
13 production; 2) increased evapotranspiration (ET) (i.e., green water) associated with feedstock
14 production; 3) increased landscape N application rates for feedstock production; and 4) increased
15 land area requirements for feedstock production. Each of these impact metrics is presented as a
16 function of both gross ethanol yield (i.e., per 1000 L EtOH) and net ethanol energy yield (i.e.,
17 per net GJ EtOH), providing a straightforward comparison of relative feedstock impacts
18 associated with volumetric production (i.e., gross yield) goals and a more holistic comparison of
19 impacts in terms of fossil fuel demand reduction (i.e., net yield). Regional water resource
20 implications of biofuel production at volumetric levels for 2022 RFS mandates and net fossil fuel
21 offset scenarios are presented and discussed.

22

23 **Methods**

1 Agricultural inputs (fertilizer, pesticide, herbicide, diesel, machinery, irrigation, seed,
2 labor), feedstock outputs, transportation inputs (fossil fuel and machinery), ethanol conversion
3 inputs (fossil fuel, chemicals, and machinery), and gross ethanol yields were evaluated using life
4 cycle methods commonly employed in the analysis of biofuel production (Giampietro and
5 Ulgiati 1997, Shapouri *et al.* 2002, Dias de Oliveira *et al.* 2005, Gnansounou *et al.* 2005,
6 Pimentel and Paztek 2005, Hill *et al.* 2006, Kim and Hayes 2006, Pimentel and Paztek 2007,
7 Wang *et al.* 2007; Macedo *et al.* 2008; Schmer *et al.* 2008). Our life cycle analysis was specific
8 to feedstock production and processing in Florida and Georgia, extended to include associated
9 water resource impacts.

10 Inputs and yield data were obtained from published literature on agricultural practices,
11 biofuel manufacturing, and water requirements associated with both feedstock production and
12 ethanol manufacturing (detailed input/output analyses are provided in Online Supporting Tables
13 1-6). All analyses assumed feedstock yields at the farm gate at the high end of published ranges.
14 For example, optimal corn grain yields (12,600 kg/ha) in Florida and Georgia (as suggested by
15 Wright *et al.* 2004) are 57% higher than average yields (8,050 kg/ha) reported for the two states
16 in 2007 (USDA 2008a, b) and 37% higher than yields assumed (9,300 kg/ha) in a recent life
17 cycle analysis of Midwestern corn ethanol (Hill *et al.* 2006). Similarly, maximum sweet sorghum
18 yields of 109,000 kg/ha fresh weight (32,700 kg/ha dry weight) (Tew and Cobill 2006) are more
19 than twice the mean yields assumed in a past study of sweet sorghum ethanol in the southeast
20 U.S. (Rains *et al.* 1993) and a more recent study of sweet sorghum ethanol production in China
21 (Gnansounou *et al.* 2005). Sugarcane yields were based on data from the Everglades Agricultural
22 Area (EAA), which has soils and climate that are much more appropriate for intensive sugarcane
23 production than other areas of Florida and Georgia (Baucum *et al.* 2006). Pine forestry yields are

1 based on wood output reported for high intensity cultivation in the southeast over a 25 year
2 rotation (Johnson *et al.* 2005), thus representing an upper bound of recoverable wood biomass.

3 As with all life cycle analyses, results are predicated on model assumptions, including
4 those about feedstock and ethanol yields, production inputs and co-product credits. To examine
5 the sensitivity of our model results to these assumptions, we recomputed the key metrics for
6 three scenarios in contrast to the base case. First, we evaluated the impacts of lower yields by
7 using mean yields per area for each feedstock rather than the high end of observed values.
8 Second, we evaluated each process and determined the input assumptions that most influenced
9 the life-cycle metrics; we first varied those inputs to each process that might lead to
10 underestimating the life cycle costs (co-product credits for corn, N fertilization for sugarcane and
11 sweet sorghum, enzyme use in cellulose conversion for pine), and second varied inputs that
12 might overestimate those costs (stover utilization in corn-to-ethanol conversion, reduced
13 transport costs for sugarcane and sweet sorghum, reduced enzyme use for pine). Finally, we
14 evaluated the effects of plausible increases in gross conversion efficiency (i.e., L of EtOH per kg
15 of feedstock) for all feedstocks, reasoning the current extraction methods may be improved,
16 particularly for cellulosic ethanol.

17

18 *Energy Balance*

19 Energy balance calculations were made per unit area (1 hectare area). Agricultural inputs
20 were converted to fossil energy equivalents using conversion factors from a recently published
21 life cycle analysis for corn ethanol (Hill *et al.* 2006). Transportation costs for feedstocks to and
22 ethanol from the production facility were based on transport distances and mean per distance
23 energy consumption (Shapouri *et al.* 2002). Energy costs for feedstock conversions were based
24 on a dry mill process for corn (Hill *et al.* 2006), a whole cane process for sugarcane (Shapouri *et*

1 *al.* 2002), on-farm juice extraction and juice conversion for sweet sorghum (Grassi *et al.* 2002,
2 Renegie Inc. 2007), and acid pre-treatment and staged enzymatic hydrolysis for wood (Kim and
3 Hayes 2006, STCI 2006). The life-cycle net energy benefit ratio (NEBR) was determined by
4 dividing gross ethanol output in energy units per hectare by the fossil fuel equivalent input
5 requirements. When determining the gasoline displacement of ethanol produced on a net energy
6 basis, we used the life-cycle energy costs of gasoline where each unit of energy delivered
7 required 0.2 energy units to extract, refine, and transport the fossil fuel (Wang *et al.* 2007).

8 Additional energy output credit was given for marketable co-products (Online Supporting
9 Table 5). Corn ethanol is given co-product credit for dried distiller grain, a high protein animal
10 feed, through a calculation of the fossil energy required to produce alternative feed products (Hill
11 *et al.* 2006). Sugarcane and pine ethanol processes both have a co-product of exported electricity
12 obtained through combustion of residual biomass (sugarcane bagasse and wood lignin,
13 respectively) in biofuel refineries. This electricity export is credited as the energy equivalent of
14 the natural gas demand displaced within the power grid. The sweet sorghum ethanol process has
15 a co-product of cellulosic biomass remaining after on-farm juicing, which is then processed into
16 agro-pellets that can be combusted in a biomass power plant. Similar to the export electricity
17 credit for sugarcane and pine processes, sweet sorghum agro-pellets are credited for displacing
18 natural gas demand in electricity production. Although natural gas currently comprises only 43%
19 of Florida's electricity production and 9% of Georgia's, we assume natural gas displacement in
20 electricity co-product calculations due to the fact that peak load capacity increases in the two
21 states have been largely provided by construction of natural gas-fired facilities. NEBR with co-
22 products for all feedstocks was calculated by adding co-product energy credits to ethanol output
23 and dividing by energy inputs.

24

1 *Environmental Resource Use*

2 For life-cycle assessment of environmental impacts, selection of baseline conditions
3 against which new scenarios are evaluated is critically important. For this analysis, we evaluate
4 the impacts assuming that future feedstocks are produced on lands that are currently used at low
5 intensity (i.e., current pine plantations, low intensity pasture, abandoned agricultural land,
6 existing conservation lands). As such, the impacts are new, and not offset by impacts accruing
7 from current land uses. The delineation of which lands would be used for feedstock production
8 and which retained for their current use is well beyond the scope of this analysis, but is of critical
9 importance for future research.

10 Water resource impacts refer collectively to impacts on human appropriation of
11 freshwater resources and impacts on water quality; by association, and because of the spatially
12 distributed nature of bioenergy production, our life cycle analysis also includes impacts on land
13 resource allocation. Gross land requirements vary by feedstock, annual agronomic productivity
14 and ethanol conversion efficiency (Online Supporting Table 6). For corn, sweet sorghum, and
15 sugarcane, yields were for an annual harvest cycle. In the case of southern pine, production
16 output for a 25 year rotation was annualized to determine the land area that must be in
17 continuous production to meet ethanol demands. Land requirements for gross yields ($\text{m}^2/\text{GJ}_{\text{gross}}$)
18 were computed directly from estimated biomass yields and conversion efficiency. Land
19 requirements for net energy production ($\text{m}^2/\text{GJ}_{\text{net}}$) were computed by multiplying the land area
20 per gross yield by the $[(\text{NEBR})/(\text{NEBR} - 1)]$, both with and without co-product credits (Online
21 Supporting Table 7).

22 Water requirements were based upon direct withdrawals for irrigation and ethanol
23 processing (i.e., “blue” water, or water withdrawn from surface and subsurface stores; Rost et al
24 2008), and the amount of additional rainfall used for evapotranspiration during feedstock

1 production as compared to displaced or reference ecosystems (i.e., “green” water). While direct
2 appropriation of blue water resources to facilitate high feedstock yields is the most obvious use
3 of water, it is increasingly understood that green water use by unirrigated biomass production
4 systems also has critical implications for water resources at a landscape level (Powell *et al.* 2005,
5 Berndes 2008). The evapotranspiration rate found in natural pine savanna and low intensity
6 pasture was used as the reference for corn, sweet sorghum and southern pine feedstocks, while a
7 monotypic sawgrass marsh was used as the reference ecosystem for muck soil sugarcane
8 production. For irrigated feedstocks, blue water use was subtracted from green water use to
9 enumerate evapotranspiration demand being met through irrigation, rather than rainfall; total
10 water use was the sum of green and blue water. Because irrigation rates for corn and sugarcane
11 exceed estimated green water demand, green water use for these feedstocks was assumed to be
12 zero. Given ethanol yields and crop water use per area (plus comparatively small quantities used
13 in industrial processing), water use for gross ethanol production was determined (Table 1; Online
14 Supporting Table 6). As with land, the NEBR for each feedstock was used to estimate water
15 resource demands on a net energy basis (Online Supporting Table 7).

16 Nitrogen loading was based on fertilizer application recommendations (as N) to achieve
17 high end yields. Application rates rather than loss rates were used because agronomic N use
18 efficiencies necessary to estimate losses are highly spatially and temporally variable, subject to
19 soil type, climatic conditions, relief, and, in the case of forest operations, stand age. Moreover,
20 existing data on N use (from fertilizer sales) provides a more accurate benchmark against which
21 to compare future loading than does landscape N export in rivers, for which estimates are
22 intrinsically less certain. While fertilizer application rates provide a basis for comparing
23 eutrophication potential from biofuel feedstocks, the results may exaggerate the impacts of N
24 loading from feedstock systems with high N uptake efficiency and/or low mineral N export rates

1 (e.g., southern pine production forests). As with water use, gross ethanol yields and N loading
2 rates per area provided the basis for determining N requirements for gross production (Table 1;
3 Online Supporting Table 6), while NEBR values (Online Supporting Table 5) were used to
4 estimate net energy N loading (Online Supporting Table 7).

5 While the analysis here focuses on N loading to the hydrologic system, we acknowledge
6 that phosphorus (P) loads from feedstock production may be more problematic for freshwater
7 eutrophication in many areas (Carpenter et al. 1998). However, the presence of naturally
8 occurring phosphatic geologic deposits in Florida and, more generally, the complexity of soil P
9 leaching make generalizations about the regional impacts of P loading significantly more
10 uncertain than those for N (Cohen et al. 2008). As such, we suggest that a watershed-based
11 approach is more appropriate than a regional analysis for determining P eutrophication risk from
12 increased biofuel production in Florida and Georgia.

13

14 **Results**

15 *Feedstock Energy Balances*

16 Feedstock input requirements for corn, sugarcane, sweet sorghum and southern pine
17 cultivation in Florida and Georgia (Online Supporting Tables 1-4) differ in both total magnitude
18 and relative importance. Total energy inputs at the farmgate – that is, post-harvest, but pre-
19 transport – are 7.47, 4.97, 7.33 and 2.03 MJ per liter of overall ethanol yield, respectively. Direct
20 combustion of fossil fuels, primarily as diesel, represents the largest feedstock energy input for
21 pine, sugarcane, and sweet sorghum; N fertilizer is the largest input for corn production.
22 Feedstock production inputs range from 24% of total life cycle energy costs for pine, 36% for
23 corn, 44% for sweet sorghum, to a high of 57% for sugarcane (Fig. 1).

1 Life cycle inputs for post-harvest biomass transport and ethanol conversion also vary
2 among the feedstocks (Fig. 1). Transportation costs are highest for sugarcane (3.47 MJ/liter
3 EtOH) and sweet sorghum (3.28 MJ/liter EtOH) because of rapid transport of high moisture
4 products (fresh biomass for sugarcane, juice for sweet sorghum) to ethanol facilities after harvest
5 to minimize sugar content degradation. Much lower transport costs are associated with corn
6 (0.99 MJ/liter EtOH) and pine wood chips (1.50 MJ/l EtOH), both of which are partially dried
7 before transport with no adverse effect on ethanol yield.

8 At 12 MJ/l EtOH, dry mill conversion of corn kernels is the most fossil energy intensive
9 ethanol production process considered. Fossil energy costs for conversion of other feedstocks
10 were 6 MJ/l EtOH for sweet sorghum, 5 MJ/l for pine wood chips, and 0.28 MJ/l for sugarcane
11 (Online Supporting Table 5). Power provided from combustion of non-fermentable feedstock
12 biomass at the ethanol facility significantly reduces fossil energy needs for both wood and
13 sugarcane processes.

14 The sum of agricultural inputs, post-harvest transport, and ethanol conversion in
15 comparison with gross ethanol yields (Fig. 1, Online Supporting Table 5) suggests that all four
16 feedstocks generate net energy (i.e., NEBR > 1.0) on a fossil fuel equivalent basis, even
17 neglecting co-products. Southern pine had the highest NEBR with values near 3 (2.97:1) for
18 ethanol production with an electricity co-product and 2.49:1 for ethanol without co-product
19 credit. Sugarcane and sweet sorghum NEBRs were 2.51 and 1.94:1, respectively, with inclusion
20 of co-product credits. Sugarcane maintains a relatively high NEBR of 2.44:1 when co-products
21 are not considered, but sweet sorghum falls significantly (1.28:1). Corn, which had an NEBR of
22 1.26:1 after co-product credit for dried distiller grains and only 1.05:1 when excluding co-
23 products, is clearly the most energy intensive of the four feedstocks.

24

1 *Feedstock Water Resource Demands*

2 Land, N, and water requirements for gross ethanol and net energy production vary among
3 feedstocks (Fig. 2; Online Supporting Tables 6-7). Southeastern corn had the highest gross and
4 net resource demand for most categories; total water demands for net energy production are
5 approximately an order of magnitude higher than for other feedstocks (Fig. 3). Both sugarcane
6 and sweet sorghum, crops with high productivity and ethanol conversion efficiency, are notable
7 for relatively low land demands on a gross and net yield basis. Because much of the net energy
8 yield for sweet sorghum is from co-product credit, water demands for sweet sorghum when
9 considering only the net energy return from ethanol are higher than either sugarcane or pine (Fig.
10 3). While N fertilizer demands are low for sugarcane in the Everglades Agricultural Area (EAA),
11 expansion of sugarcane production into areas with non-peat soils would require significantly
12 higher N fertilization rates (Table 1; Online Supporting Table 9). Pine feedstocks have low N
13 and negligible blue water demand, but high land use and green water requirements in relation to
14 other feedstocks on a gross yield basis. Total water required for pine ethanol is less than other
15 feedstocks when considered on a net energy basis (Fig. 3).

16

17 *Water Resource Implications of RFS: 2022*

18 The RFS mandates 136 billion liters of biofuel production nationally in 2022. If this
19 mandate is fulfilled entirely by ethanol, the volumetric production would be energetically
20 equivalent to approximately 17% of U.S. gasoline consumption in 2007 (EIA 2008). Using the
21 assumption that regional biofuel production will be proportional to regional gasoline
22 consumption (and assuming no growth in regional consumption), biofuel outputs for Florida and
23 Georgia in 2022 should be approximately 10% of RFS mandates, or 13.6 billion liters (EIA
24 2008).

1 Given existing economic uses of agricultural and forestry lands, provision of sufficient
2 feedstocks to meet 2022 RFS production levels clearly has the potential to result in displacement
3 of natural areas already under pressure from agricultural and urban development. For example,
4 achieving 13.6 billion liters of ethanol production would require at least 6% of total land area in
5 Florida and Georgia be dedicated to feedstocks with high gross yields (i.e., sugarcane or sweet
6 sorghum), with all biomass output used solely for ethanol production (Table 1). By way of
7 comparison, existing sugarcane cultivation in the EAA – which produces over half the US sugar
8 crop – amounts to only 0.6% of the total land area of Florida and Georgia. Over 16% of total
9 land area (31% of current forest land) in the two states would be required if pine were utilized as
10 the sole feedstock to meet these relatively modest volumetric production goals (Table 1).

11 Total water demand and N use also increase significantly to meet 2022 RFS production
12 targets. Estimated blue water requirements for sweet sorghum, the most water-efficient
13 agricultural crop considered in this study, would increase by almost 25% total freshwater
14 withdrawals for all human uses reported in Florida and Georgia for 2000; corn and sugarcane
15 would require well over twice this water volume. Pine forestry is not irrigated; all blue water use
16 is associated with ethanol conversion. However, estimated green water consumption for pine
17 production to meet biomass requirements for RFS targets would amount to almost 60% of water
18 withdrawals reported for 2000, which would be likely to have important implications in terms of
19 reducing regional stream flows.

20 N fertilizer use associated with feedstock production sufficient to meet RFS targets would
21 be most dramatic for corn, which would necessitate additional N loading to the landscape of
22 nearly 1.5 times the application rates for all land uses during 2000. Nitrogen demands for sweet
23 sorghum and sugarcane (the latter adjusted to agronomic requirements outside the EAA) are
24 significantly less than corn, but N loading for either crop exceeds 60% of total N use in the

1 region in 2000. N requirements for pine feedstock production are relatively small in comparison
2 to crop feedstocks, but would still require a 16% increase in total N use vis-a-vis use in 2000.

3

4 *Water Resource Costs for Fossil Energy Replacement*

5 While it is instructive to consider resource impacts in terms of gross volumetric yields,
6 comparisons of water use (Fig. 3), land use, and water quality impacts (Fig. 4) on a net energy
7 basis have the advantage of estimating environmental resource demands for actual fossil energy
8 displacement. On a gross basis, producing 13.6 billion L of ethanol will displace approximately
9 17.5% of current gasoline consumption. Due to differing NEBR values for each feedstock, net
10 displacement of fossil fuel energy (using 2007 gasoline consumption and including the embodied
11 energy in gasoline – Wang et al. 2007) associated with that 13.6 billion L of production would be
12 highest for pine (~14.0%), somewhat less for sugarcane (~12.7%) and sweet sorghum (~10.2%),
13 and lowest for corn (~4.4%) in the context of Florida and Georgia (Table 1).

14 Land use and water resource challenges for large-scale ethanol production are made
15 evident by our estimate that sweet sorghum-to-ethanol, the most efficient of the four feedstocks
16 considered in terms of total water consumption and land area, would require water appropriation
17 equal to total water withdrawals for all human uses reported in 2000 at approximately 40% net
18 liquid fuel replacement (Fig. 3). Similarly, achieving 100% net liquid fuel replacement would
19 require optimum sorghum yields on 49% of the land area in the two states (Fig. 4) and water use
20 that is approximately 2.5 times higher than total current freshwater withdrawals (Fig. 3). There is
21 insufficient land area for either corn or pine forestry to replace 100% of current liquid fuel
22 consumption on a net basis (Fig. 4). Significant implications are also evident for water quality:
23 anthropogenic N use would double at roughly 50% net liquid fuel replacement using pine
24 forestry, the least intensively fertilized feedstock.

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Ethanol Potential from Waste Biomass

Utilization of existing waste biomass resources for biofuel production represents a largely untapped source that could reduce primary feedstock demand, and which would presumably have high NEBR values. Recent estimates of solid phase waste biomass (crop residues, forest residues, primary and secondary wood mill residues, urban wood residues, and energy crops – primarily switchgrass – grown on Conservation Reserve Program (CRP) lands) produced in each county yield a total mass 23.7 million tons per year for Georgia and Florida (Milbrandt 2005). This value represents the upper bound of biomass available annually for ethanol conversion without changes in existing land use and, aside from processing demands, direct water resource impacts. Assuming an ethanol conversion rate of 300 liters per dry ton, conversion of all waste biomass to ethanol would yield, on a gross basis (net energy estimates are not available), energy equivalent to 32.7% of the 2022 RFS allocation for Florida and 88.2% of the 2022 RFS allocation for Georgia, or approximately 9.2% of 2006 gasoline consumption for the two states (Online Supporting Table 8).

Sensitivity Analysis

Life cycle metric sensitivity to input and process assumptions is substantial (Online Supporting Table 9). Reducing crop yields from highly generous assumed levels to more likely nominal yields lowers the NEBR and raises the environmental metrics (land, water and and N use per net energy yield) for all feedstocks, with the most dramatic effects observed with corn. Raising N fertilization rates for sugarcane and sweet sorghum to rates that presumably would be necessary for sustaining high yields on mineral soils dramatically increased N use per net energy (0.4 to 2.3 and 1.4 to 2.7 kg N/GJ_{net}, respectively), but had significantly less effect on NEBR,

1 water use, and land use (~ 15% change). Similarly, while decreasing transportation costs by a
2 factor of 5 for both sugarcane and sweet sorghum increased NEBR dramatically (~ 25-40%
3 increase), the effect on water, land and N use was far less significant (~10% decrease). The key
4 input assumption for pine was the addition of enzymes to convert celluloses to fermentable
5 sugars; the published range of inputs is 0.04 to 0.81 kg/L EtOH (STCI 2006), from which we
6 assumed 0.22 kg/L for the baseline scenario. The effect of this is dramatic, with NEBR varying
7 between 1.96 and 5.14 in response to that range, and water use per net energy decreasing by a
8 more than 40% at low levels of enzyme use. Increases in the gross ethanol conversion rate result
9 in somewhat higher NEBRs, but the associated increases in ethanol output per hectare lead to far
10 more significant implications in terms of reducing overall land, water, and nitrogen demands.
11 Such effects are particularly pronounced for the pine ethanol process, as large reductions in
12 environmental life cycle demands occur when conversion efficiency is increased from the base
13 case of 0.257 l EtOH/kg to a technically plausible 0.30 l EtOH/kg.

14

15 **Discussion**

16 Meeting the RFS mandates with primary feedstocks will engender important
17 environmental trade-offs. While our results suggest major differences between feedstocks
18 regarding water resource impacts, net fossil energy displacement potential, and scale-up
19 feasibility, it is also apparent that biofuel production in Florida and Georgia from any of the four
20 feedstocks considered would have significant impacts on both land use and water resources when
21 scaled up to RFS levels of gross production. It is also clear that the impacts accrue principally
22 from feedstock production rather than from fermentation and distillation; for example, water use
23 in a modern distillery (~10 L water per L of ethanol) is just over 1% of the total life-cycle water
24 use estimated for pine ethanol production. Moreover, it is likely that actual land use and water

1 resource impacts of feedstock production may be somewhat higher than our results suggest,
2 mainly due to our use of generous assumptions regarding agronomic output potential. Additional
3 environmental impacts from phosphorus loading, soil erosion and/or oxidation, and loss of
4 wildlife habitat – while not explicitly considered in this analysis – are also implied by increased
5 biofuel feedstock production. All these potential impacts should be considered when comparing
6 relative costs and benefits of different candidate feedstocks and in developing policy to manage
7 water supply and pollutant-load demands that will accompany large scale production.

8 Corn currently dominates U.S. ethanol production. Although most recent studies show a
9 positive, but generally small, NEBR from corn ethanol, there is growing concern about negative
10 externalities of increased corn ethanol production, including high N and pesticide loading,
11 upward pressure on grain prices, and rapid conversion of lands previously held in the CRP
12 (Pimentel and Patzek 2005, Hill *et al.* 2006, Tilman *et al.* 2006, NRC 2007, Donner and
13 Kucharik 2008, Fargione *et al.* 2008, Searchinger *et al.* 2008). In the southeast, our study
14 suggests that corn is notable for high blue water and N fertilizer requirements and low NEBR
15 compared to other feedstocks, even under the assumption of very high optimum corn yields. A
16 sensitivity analysis using yield of 7875 kg/ha, which is a more plausible average corn yield for
17 the southeast than the optimum number we use in our base case, gives an NEBR with co-product
18 of only 1.03 (Online Supporting Table 9). Given consistently low NEBR values, high
19 environmental resource requirements, and limited future potential for increasing biofuel process
20 efficiency, corn represents the least desirable option for large-scale ethanol production in the
21 southeast.

22 Sugarcane is the primary feedstock for ethanol production in Brazil, the world's second
23 largest ethanol producer. Our estimated NEBR of 2.51 for sugarcane ethanol corroborates
24 numerous studies that suggest sugarcane ethanol conversion is more efficient than corn ethanol

1 (Dias de Oliveira *et al.* 2005, Hill *et al.* 2006, Macedo *et al.* 2008). This result is significantly
2 higher than the NEBRs reported in a recent analysis of sugarcane ethanol in Louisiana and Brazil
3 (Pimentel and Patzek 2007), but lower than the NEBR values of 3.7:1 (Dias de Oliveira *et al.*
4 2005) and 9.3:1 (Macedo *et al.* 2008) reported in two recent studies of Brazilian sugarcane
5 ethanol. Discrepancies among these studies are principally explained by differences in energy
6 intensity of reported agricultural inputs and transportation efficiency. Estimates of agricultural
7 inputs for Brazilian sugarcane range from a low of 10.8 GJ/ha (Macedo *et al.* 2008) to a high
8 value of 35.8 GJ/ha (Dias de Oliveira 2005). Because Brazil is generally considered to be among
9 the world's most efficient producers of sugarcane (Bolling and Suarez 2001), it is not surprising
10 that our estimate of agricultural energy inputs into Florida sugarcane (38.3 GJ/ha – Online
11 Supporting Table 2) is somewhat higher than those reported for Brazil. Differences between the
12 sugarcane agriculture energy inputs in our study and the 56.1 GJ/ha of agricultural inputs
13 reported by Pimentel and Patzek (2007) for Louisiana sugarcane are largely explained by the
14 much lower nitrogen fertilizer requirements in the organic soils of the EAA (40 kg/ha in the
15 EAA vs. 196 kg/ha in Louisiana). Our transportation energy cost of 0.25 MJ/kg for sugarcane
16 biomass (and all other feedstocks) is based on biomass transport distance data for existing U.S.
17 corn ethanol manufacturing facilities (Shapouri and Salassi 2006). The resultant energy cost for
18 transporting Florida sugarcane using this method is five times greater than the cost (0.05 MJ/kg)
19 reported by Macedo *et al.* (2008) for Brazilian sugarcane ethanol, but one half the transport
20 energy cost (0.5 MJ/kg) reported by Pimentel and Patzek (2007) for both Brazilian and Louisiana
21 sugarcane ethanol. Given that the location of ethanol plants and, by extension, the crop hauling
22 distance for feedstocks in Florida and Georgia is unknown at this time, we believe that the most
23 straightforward comparison of feedstocks is provided by the standardized mass-based
24 transportation energy cost that we use. NEBR for Florida sugarcane ethanol does increase

1 significantly to 3.49:1 if transport energy costs for sugarcane are reduced to the level suggested
2 by Macedo *et al.* (2008), thereby reducing the land area requirements from 98 to 83 m²/GJ_{net} and
3 total water use from 72 to 61 m³/GJ_{net} (Online Supporting Table 9).

4 Despite consensus that the NEBR from sugarcane is significantly higher than from corn,
5 use of the existing Florida sugarcane crop as a dedicated ethanol feedstock has been generally
6 regarded as uneconomical, mostly due to government price supports that inflate the price of U.S.
7 sugar relative to the world market (Shapouri and Salassi 2006). It is also relevant that the biofuel
8 potential of existing Florida sugarcane is small: allocation of all existing sugarcane production in
9 the EAA (162,000 ha) to ethanol would produce only 1.25 billion liters EtOH/yr, approximately
10 11% of the 2022 RFS allocation for Florida and Georgia, and less than 2% of current gasoline
11 consumption. Moreover, costs of mitigating downstream phosphorus loading to the Everglades
12 and ongoing peat soil oxidation in the EAA are two additional challenges to using sugarcane as a
13 bioenergy crop in south Florida. Regional scale-up scenarios for sugarcane, which already show
14 high water use, are optimistically based on EAA crop yields. Large-scale sugarcane production
15 in Florida and Georgia outside the EAA certainly requires larger fertilization inputs and,
16 although insufficient data are available for an independent life cycle analysis of non-EAA
17 sugarcane, is also likely to have lower productivity and NEBR values than those shown in our
18 sensitivity analyses (Online Supporting Table 9).

19 Sweet sorghum is widely viewed as a promising feedstock due to low fertilizer and water
20 requirements compared to corn and sugarcane. Our results support this contention; sweet
21 sorghum exhibits high productivity, low land use requirements, and, by extension, low total
22 water requirements in comparison to other feedstocks. Although total ET is similar to corn (~
23 700 mm over 120 days), blue water requirements for sweet sorghum are lower (250 mm vs. 500
24 mm) because, unlike corn, transient wilting stress can be tolerated without adverse effects on

1 yield (Steduto *et al.* 1997). As such, irrigation schedules for sweet sorghum can be reactive to
2 dry conditions, rather than precautionary, as is generally necessary with corn in the U.S.
3 southeast (Wright *et al.* 2004). Large quantities of fossil energy in the sweet sorghum process are
4 diesel fuel for harvest, juicing, and juice transportation. As such, increased machine efficiency
5 and minimization of transport distances offer the clearest opportunities for boosting NEBR
6 values.

7 However, important unanswered questions remain for sweet sorghum ethanol. Like other
8 feedstocks, estimates of land requirements for sweet sorghum are based on scaling up optimal
9 yields of 32.7 dry tons per hectare (Tew and Cobill 2006) that are unlikely to be achieved on a
10 consistent basis across sites. Furthermore, it seems unlikely that relatively low published N
11 fertilization rates of 160 kg/ha (Mylavarapu *et al.* 2007) are sustainable given a harvest process
12 that utilizes all above ground biomass for biofuel production (i.e., ethanol plus agro-pellets).
13 Assuming optimal sweet sorghum yields, N loss rates from harvest are 300 – 330 kg/ha (Soileau
14 and Bradford 1985, Barbanti *et al.* 2006), twice the suggested fertilization rate, even without
15 taking into account N losses due to volatilization and leaching. While a higher N fertilization rate
16 only slightly lowers the NEBR value of the biofuel process from 1.94:1 to 1.83:1, N loadings to
17 the environment for biofuel return almost double from 1.4 kg N/net GJ to 2.7 kg N/net GJ
18 (Online Supporting Table 9). In short, NEBR and environmental resource use estimates for
19 sweet sorghum must be considered provisional until full-scale production examples are
20 evaluated.

21 Development of ethanol from cellulosic feedstocks, such as wood and fibrous grasses,
22 which can be grown on lands not suitable for large-scale food production is a clear priority for
23 economical and environmentally sustainable production. The EISA contains provisions to
24 encourage U.S. cellulosic ethanol production beginning in 2012, and a number of facilities using

1 cellulosic feedstocks such as switchgrass, wood, and agricultural residues are currently under
2 construction or in pre-construction planning throughout the U.S. One facility based on
3 conversion of pine wood to ethanol is under construction in southern Georgia and, if opened on
4 schedule in 2008, will be the first commercially operational cellulosic ethanol plant in the U.S.

5 The NEBR for pine-based ethanol (2.97:1) is highest of the four feedstocks. This result
6 contrasts sharply with the 59% net energy loss for a wood to ethanol process as reported by
7 Pimentel and Patzek (2005). This discrepancy is largely attributable to the inclusion of electricity
8 and steam as exogenous inputs to the ethanol production process in the Pimentel and Patzek
9 (2005) study, while our analysis assumes cellulosic ethanol facilities designed to utilize residual
10 lignin combustion for supplying all power needs in the facility and to yield excess electricity as a
11 co-product export (Kim and Hayes 2006, STCI 2006, Schmer *et al.* 2008). At the same time,
12 several other recent studies of cellulosic feedstock such as switchgrass (Schmer *et al.* 2008) and
13 low intensity prairie grasses (Tilman *et al.* 2006) show significantly NEBRs higher than we
14 report for southern pine. This difference is attributed to our inclusion of the energetic costs of
15 cellulase enzymes in the conversion process (STCI 2006) – a cost that it is not explicitly included
16 by most other studies (Tilman *et al.* 2006, Schmer *et al.* 2008). Our base case assumption of the
17 enzyme mass required per liter of ethanol produced (0.22 kg/L) from woody biomass is
18 relatively conservative, as recent estimates range from 0.04 to 0.81 kg/L (STCI 2006). Although
19 a lowering of enzyme application rate from 0.22 kg/L to 0.04 kg/L dramatically raises the NEBR
20 to 5.14:1, corresponding reductions in land (209 to 173 m²/GJ_{net}), and associated water use from
21 (51 to 43 m³/GJ_{net}) are relatively small. By contrast, changing the assumed gross conversion
22 efficiency from 0.257 L EtOH/kg biomass to 0.30 L EtOH/kg biomass while still using the base
23 case level of enzyme has the effect of reducing the land footprint from 209 to 175 m²/GJ_{net} and
24 associated water use from 51 to 43 m³/GJ_{net}. That is, an approximate doubling of the NEBR by

1 assuming no energy cost for enzymes has approximately the same effect on land and water use as
2 increasing the gross ethanol conversion efficiency by 20%. We infer that overemphasizing the
3 NEBR could lead to sub-optimal decisions about feedstocks and production processes; indeed,
4 where the NEBR is larger than 2, increases of gross yield progressively become much more
5 important than net energy yield in terms of reducing environmental impact metrics from
6 feedstock production.

7 A distinct disadvantage of pine feedstock is comparatively low agronomic productivity
8 per unit area and high associated green water demands for large-scale production. Given existing
9 economic utilization of pine forest products in the southeast, additional demand for cellulose
10 associated with large-scale ethanol production is likely to place production pressure on
11 remaining natural forest lands – which may be viewed as both a source of biomass standing crop,
12 and land area that can be converted into high intensity forestry. While impacts of green water
13 consumption may not be as immediately apparent as direct blue water withdrawals, it is clear that
14 increased cover of high intensity plantation forestry can significantly lower regional water tables,
15 reduce stream flows, and, by extension, potentially affect water supplies and aquatic ecosystem
16 function (Jackson *et al.* 2005, Powell *et al.* 2005); estimates of stream flow reduction following
17 afforestation are roughly 250 mm per year, which is the excess ET value we attribute to high
18 intensity pine (Powell *et al.* 2005).

19 It is also clear from these results that a significant fraction of the biomass necessary to
20 achieve RFS mandates will need to be met with dedicated feedstocks. While waste biomass can
21 reasonably be used for some production, significant economic and energetic costs associated
22 with the concentration and transportation of diffuse biomass sources currently – and perhaps
23 inherently – limit large-scale use of waste biomass for ethanol production (Perlack 2005,
24 Gallagher *et al.* 2003). Moreover, estimated gross yields (equivalent to 50% of RFS mandates)

1 will be markedly reduced if evaluated on a net energy basis. Other potential uses for waste
2 biomass sources, including combustion for electrical power generation, are gaining momentum
3 and may reduce available supply for ethanol (Perlack 2005). Finally, though waste biomass is
4 often regarded as a free source of energy, appropriation of crop and forestry residues for biofuels
5 implies that such residues will no longer be returned to crop and forestry lands, meaning that
6 nutrients or organic matter previously recycled through these sources must be replaced
7 (presumably through fossil fuel-based processes) if soil productivity and hydraulic properties are
8 to be maintained (Varvel *et al.* 2008). Taken together, these issues suggest that dedicated
9 feedstock production will be required to provide most of the biomass needed to fulfill RFS
10 production goals and, by extension, that future water resource impacts can be justifiably
11 estimated from land use changes required for this additional dedicated production.

12 The land use implications of large additional appropriation of landscape primary
13 production are enormous. However, our analysis stops short of addressing the particular land use
14 transitions (e.g., pasture to pine forest) that may be needed to accommodate new feedstock
15 production, and also provides no direct insight into the trade-offs that will guide decisions about
16 those transitions. Considerations of proximity to distilleries, comparative economic yields, site
17 suitability for particular feedstocks and integration within conserved land priorities will, of
18 necessity, guide land use decisions. Further research is needed to determine optimal landscape
19 configurations, and thus policy frameworks, for new feedstock production subject to those
20 multiple criteria.

21 While this work adds to the growing list of life-cycle studies contending that biomass-to-
22 ethanol processes can yield net energy, the associated water resource implications suggest a need
23 to explicitly consider environmental trade-offs associated with extensive feedstock production.
24 All feedstocks, when produced at levels required to meet RFS volumetric production goals, will

1 contribute substantially to water and land use challenges already facing the southeast. These
2 challenges are amplified when resource impacts are considered on a net energy basis, which
3 provides a more realistic assessment of fossil energy replacement than gross energy production.
4 While it is not possible in this context to adequately enumerate trade-offs between additional
5 water resource stresses on one hand and the compelling needs to limit fossil energy dependence
6 on the other, it is essential that bioenergy policy discussions explicitly recognize the strong
7 potential for conflicting priorities, and adequately plan to balance them.

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1 Table 1: Environmental resource implications of feedstock production to meet the energy equivalent of
 2 13.6 billion liters EtOH [†] production in Florida and Georgia on a gross (Gross_{EtOH}) and net energy basis
 3 (Net_{Total}; this refers to total energy output, including co-product credits, not only ethanol).

	Corn		Sugarcane ^{††}		Sweet sorghum		Pine	
	Gross _{EtOH}	Net _{Total}	Gross _{EtOH}	Net _{Total}	Gross _{EtOH}	Net _{Total}	Gross _{EtOH}	Net _{Total}
Required land (x10⁶ ha) [‡]	2.71	8.06	1.75	3.20	1.81	2.47	4.82	6.05
% Total Land Area [§]	9.4	29.9	6.1	11.0	6.2	8.5	16.7	20.9
% of Total Forest Area [¶]	17.2	54.5	11.1	19.7	11.4	15.5	30.6	38.0
N use (1000 tons) [‡]	807	2584	329	598	332	396	87	109
N use (% 2002 load) [#]	136.8	438.0	55.8	101.4	56.3	67.1	14.7	18.5
Green water (x10⁶ m³) [‡]	-	-	-	-	1,810	2,470	11,800	14,800
Green water (% 2000 use) ^{††}	-	-	-	-	9.1	12.5	59.4	75.3
Blue water (x10⁶ m³) [‡]	13400	43520	14040	21715	4650	6370	136.4	171
Blue water (% 2000 use) ^{††}	68.1	220.8	71.3	154.8	23.5	32.2	0.6	0.9
Total water (x10⁶ m³) [‡]	13400	43520	14040	21715	6460	8840	11930	14970
Total water (% 2000 use) ^{††}	68.9	220.8	71.3	154.8	32.6	44.7	60.0	76.2
Gasoline replacement (% 2007 use) ^{§§}	17.5	4.5	17.5	11.8	17.5	10.6	17.5	14.5

4 † - *Biofuels allocation*: Assumed 2022 RFS allocation for Florida and Georgia is 13.6 billion l EtOH, as
 5 these states accounted for approximately 10% of total U.S. gasoline consumption in 2006 (EIA
 6 2008).
 7 ‡ - *Resource scaling*: Gross values for land area scaled up from ha/1000 l EtOH reported in Online
 8 Supporting Table 6 to ha/1.36 x 10¹⁰ l EtOH. As 1.36 x 10¹⁰ l EtOH = 2.9 x 10⁸ GJ, net bioenergy
 9 values scaled up from m²/net GJ reported in Table 8. Similar scale up calculations performed
 10 for nitrogen, blue water, green water, and total water using gross yield values in Online
 11 Supporting Table 6 and net yield values in Online Supporting Table 7.
 12 § - *% total land area*: Land area in Florida and Georgia is 2.9 x 10⁷ ha.
 13 ¶ - *% total forest area*: Baseline forestry area of 16.3 x 10⁶ hectares in Florida and Georgia (Bugwood
 14 Network 2002, Carter and Jokela 2002).
 15 # - *% nitrogen application*: Total nitrogen applications for Florida and Georgia in 2002 are estimated at
 16 5.9 x 10⁸ kg N based on national fertilizer use (12.0 x 10⁹ kg as N) from the US Economic
 17 Research Service (<http://www.ers.usda.gov/Data/FertilizerUse>) and national and state fertilizer
 18 expenditures (US – \$9.75 billion, Florida – \$289 million, Georgia - \$190 million) from the 2002
 19 US Agricultural Census (<http://www.agcensus.usda.gov/Publications/2002/index.asp>)
 20 †† - *% water use*: Total annual freshwater withdrawals reported at 1.98 x 10¹⁰ m³ for Florida and Georgia
 21 in 2000 (Hutson *et al.* 2005).
 22 ‡‡ - *Scale-up for sugarcane* reflects an EAA fertilization rate of 40 kg N/ha on the first 162,000 ha of
 23 production and 200 kg N/ha for other required land area. Likewise, lime inputs increase from 200
 24 kg/ha to 1000 kg/ha on non-EAA lands. Assuming that yields and other inputs remain constant,
 25 associated NEBR_{Total} for non-EAA production that reflects these higher inputs is 2:13:1 (Online
 26 Supporting Table 9). Weighted NEBR_{Total} for sugarcane in scale-up scenario is thus 2.15:1.
 27 §§ - *% gasoline replacement*: For all feedstocks, gasoline replacement % in terms of Gross_{EtOH} = (1.36¹⁰ l
 28 EtOH * 21.3 MJ/l EtOH)/(5.15¹⁰ l Gas * 32 MJ/L Gas). Gasoline replacement % in terms of
 29 Net_{Total} = (1.36¹⁰ l EtOH * 21.3 MJ/l EtOH)/(5.15¹⁰ l Gas * 32 MJ/L Gas) * ((NEBR_{Total}-
 30 1)/NEBR_{Total}) * (EROEI_{Gasoline}/(EROEI_{Gasoline}-1)), where EROEI_{Gasoline} (i.e., energy return on
 31 energy invested for gasoline) is assumed at 5:1 (Wang *et al.* 2007).
 32

1 **Figure Legends**

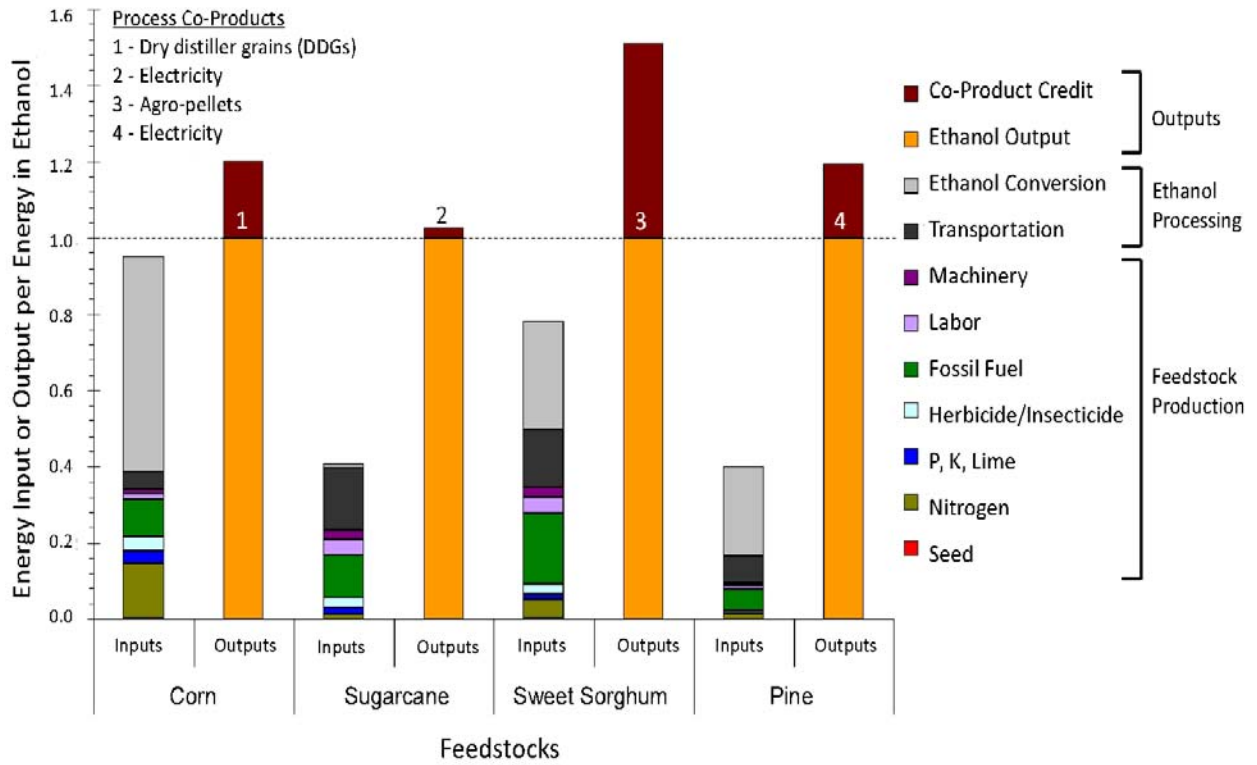
2 Figure 1. Energy inputs and outputs for ethanol production from four feedstocks. Inputs are
3 partitioned into feedstock requirements and processing/transportation. Outputs are
4 partitioned into ethanol yield and co-products production. All input and output flows are
5 scaled by the energy in ethanol (MJ/MJ).
6

7 Figure 2. Water, nitrogen and land use requirements per net energy production for four
8 Southeastern feedstocks. Values are reported after including credits for co-products.
9

10 Figure 3. Projected water use (Mg/yr) as a function of energy yield from a) corn, b) sugarcane, c)
11 sweet sorghum and d) southern pine ethanol. Lines represent water use per gross energy
12 yield (gross), per net energy yield with co-products (ethanol only), and per net energy
13 yield without co-product credits (total). Points along each line correspond to replacement
14 of 2%, 5%, 10%, 15%, 25%, 50% and 100% of current gasoline use. Current freshwater
15 water use is shown with a horizontal black line. A vertical grey line depicts the energy
16 equivalent of 2022 RFS ethanol mandates (13.6 billion L; 2.90E+08 GJ).
17

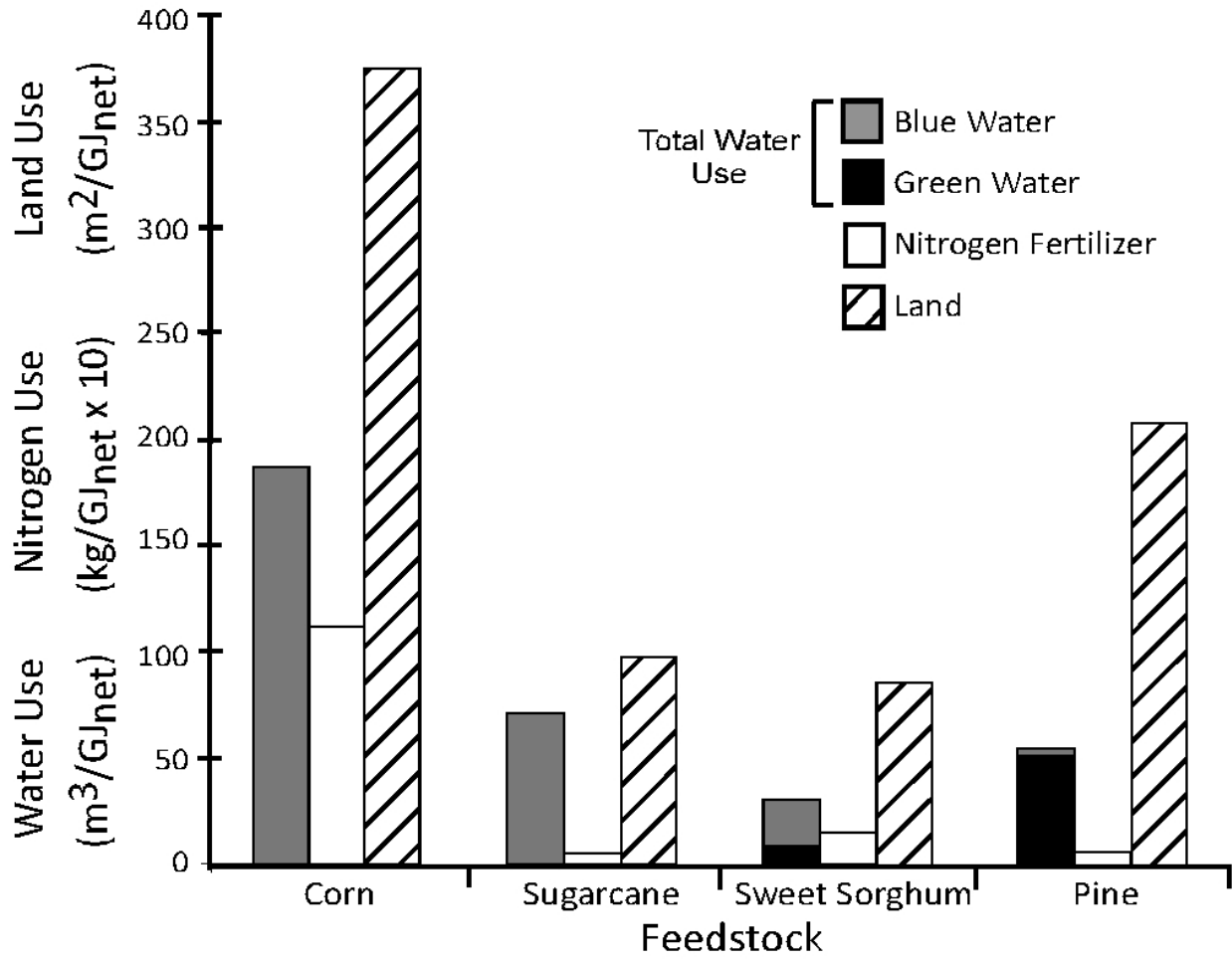
18 Figure 4. Projected use of a) N, and b) land under various gasoline offset scenarios, based on
19 total net energy production (including co-products) for four candidate feedstocks. Points
20 along each line correspond to 2%, 5%, 10%, 15%, 25%, 50% and 100% of current
21 gasoline use. Current resource use (for N) and availability (for land) are shown with
22 horizontal lines. A vertical grey line depicts the energy equivalent of 2022 RFS mandates
23 (13.6 billion L; 2.90E+08 GJ). Symbols along each grey line correspond to the resource
24 use per net energy yield for ethanol production only (i.e., no co-product credits).

1

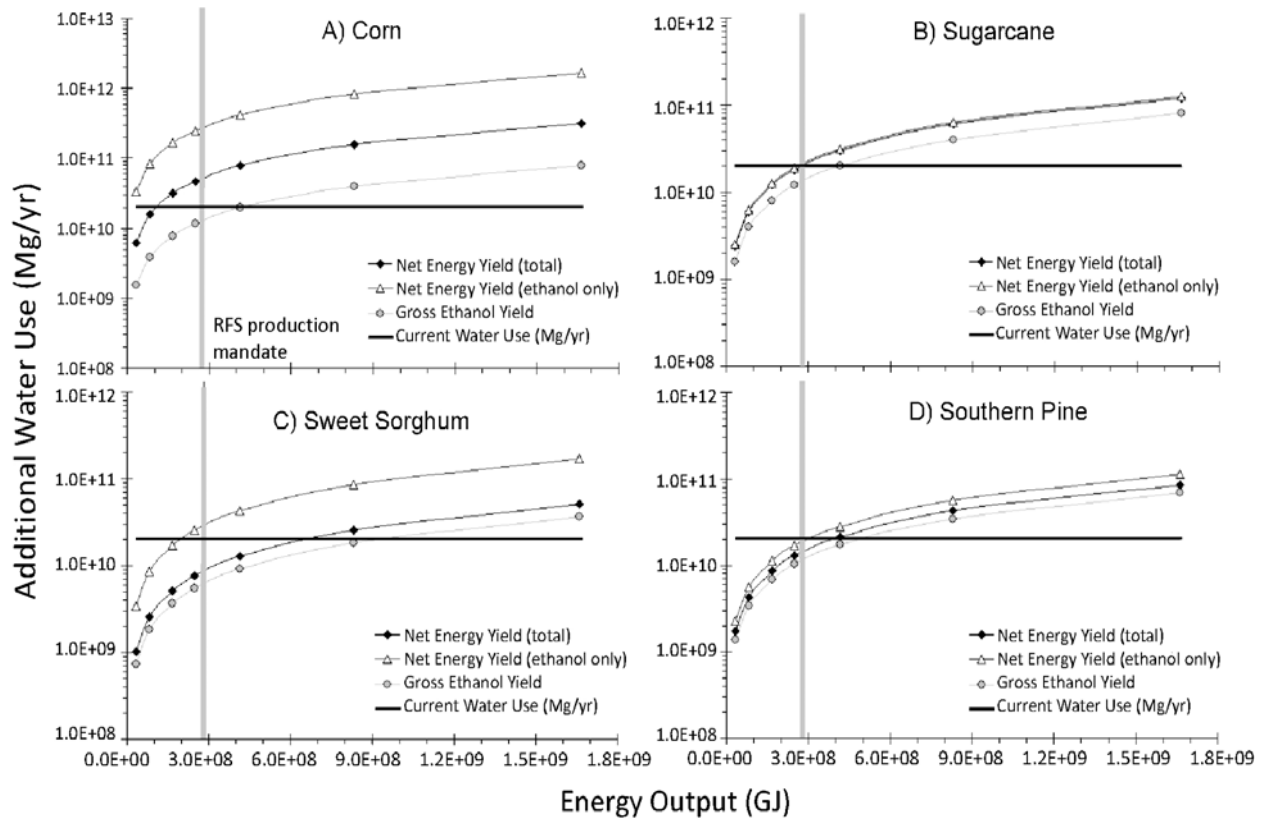


2

3 **Fig. 1**

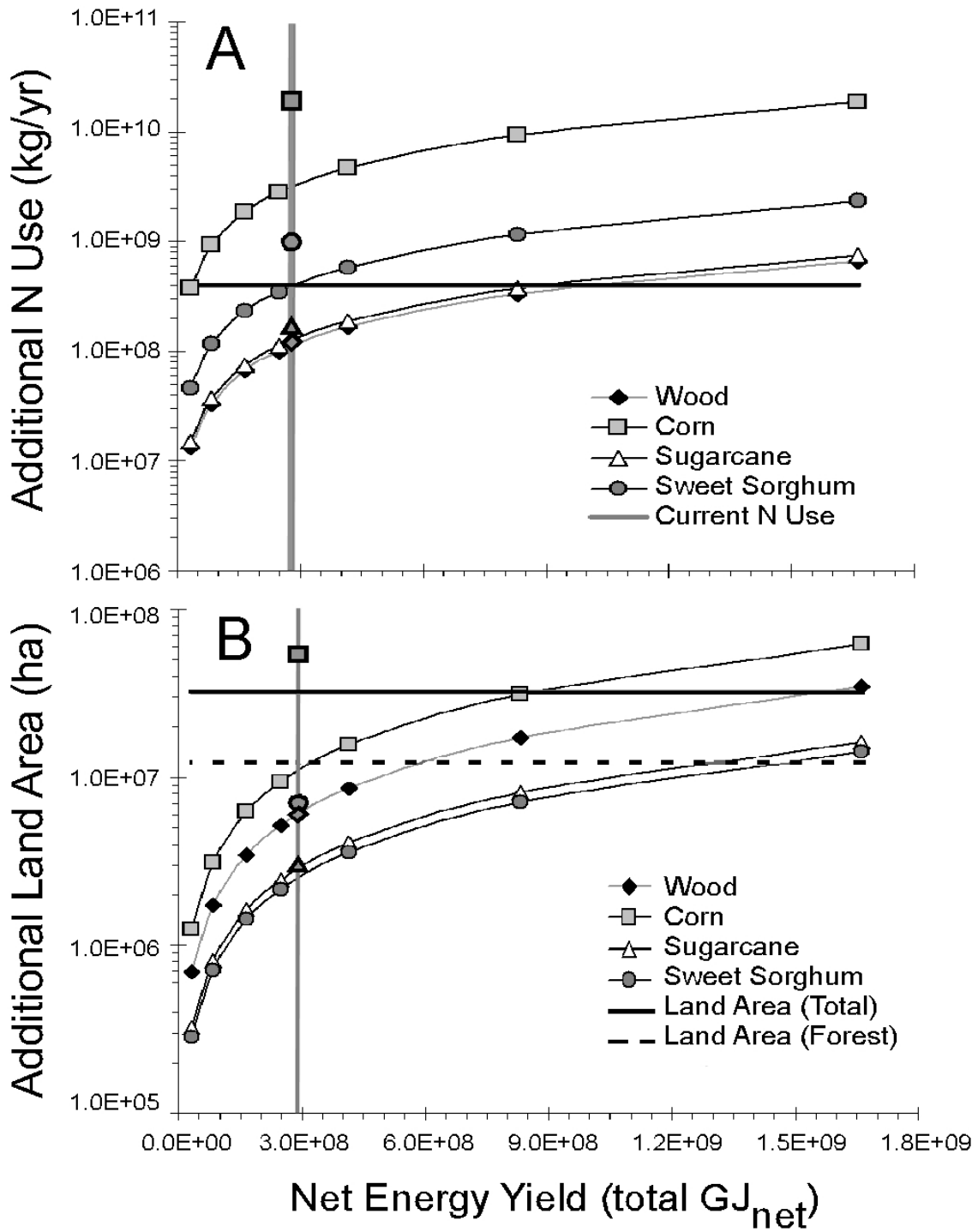


1
2 Fig. 2



1

2 **Fig. 3**



1
2 **Fig. 4**

SUPPORTING MATERIALS

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 Patzek 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.

^{‡‡} - *Labor per hectare*: (Pimentel and Patzek 2007)

^{§§} - *Machinery per hectare*: (Pimentel and Patzek 2007)

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 electricity/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 (NEBR_{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 (NEBR_{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 enzymatic 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 ($GJ_{\text{gross EtOH}}$) of ethanol and gross GJ of ethanol + co-products ($GJ_{\text{gross Bioenergy}}$) 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*: $GW_{\text{USE}} = (ET_{\text{CROP}} - ET_{\text{REF}} - I) * L_{\text{AREA}}$, 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 Co-product	Corn		Sugarcane		Sweet sorghum		Pine	
	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*: $\text{Land m}^2/\text{GJ}_{\text{net EtOH}} = (\text{m}^2/\text{GJ}_{\text{gross EtOH}}) * [\text{NEBR}_{\text{EtOH}}/(\text{NEBR}_{\text{EtOH}}-1)]$

[‡] - *Nitrogen*: $\text{kg N}/\text{GJ}_{\text{net EtOH}} = \text{Land m}^2/\text{GJ}_{\text{net EtOH}} * \text{kg N}/\text{m}^2$. 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*: $\text{Blue water}/\text{GJ}_{\text{net EtOH}} = \text{Land m}^2/\text{GJ}_{\text{net EtOH}} * I + D/\text{GJ}_{\text{net EtOH}}$, where I is irrigation water in m³/yr and D is industrial water used in ethanol production (3 liters H₂O per liter EtOH for corn; 10 H₂O per liter EtOH for sorghum, sugarcane and wood).

[¶] - *Green water*: $\text{Green water}/\text{GJ}_{\text{net EtOH}} = \text{Land m}^2/\text{GJ}_{\text{net EtOH}} * (\text{ET}_{\text{CROP}}-\text{ET}_{\text{REF}}-I)$, 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).

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