Global Change Biology (2009), doi: 10.1111/j.1365-2486.2009.01868.x

Regional water resource implications of bioethanol production in the Southeastern United States

JASON M. EVANS* and MATTHEW J. COHEN*
*School of Forest Resources and Conservation, University of Gainesville, FL, USA

Abstract

The Energy Independence and Security Act (EISA) of 2007 mandates US production of 136 billion L of biofuel by 2022. This target implies an appropriation of regional primary production for dedicated feedstocks at scales that may dramatically affect water supply, exacerbate existing water quality challenges, and force undesirable environmental resource trade offs. Using a comparative life cycle approach, we assess energy balances and water resource implications for four dedicated ethanol feedstocks – corn, sugarcane, sweet sorghum, and southern pine – in two southeastern states, Florida and Georgia, which are a presumed epicenter for future biofuel production. Net energy benefit ratios for ethanol and coproducts range were 1.26 for corn, 1.94 for sweet sorghum, 2.51 for sugarcane, and 2.97 for southern pine. Corn also has high nitrogen (N) and water demand (11.2 kg GJ_{net}^{-1} and 188 m^3 GJ_{net}^{-1}, respectively) compared with other feedstocks, making it a poor choice for regional ethanol production. Southern pine, in contrast, has relatively low N demand (0.4 kg GJ_{net}^{-1}) and negligible irrigation needs. However, it has comparatively low gross productivity, which results in large land area per unit ethanol production (208 m^2 GJ_{net}^{-1}), and, by association, substantial indirect and incremental water use (51 m^3 GJ_{net}^{-1}). Ultimately, all four feedstocks require substantial land (10.1, 3.1, 2.5, and 6.1 million ha for corn, sugarcane, sweet sorghum, and pine, respectively), annual N fertilization (3230, 574, 396, 109 million kg N) and annual total water (54 400, 20 840, 8840, and 14 970 million m^3) resources when scaled up to meet EISA renewable fuel standards production goals. This production would, in turn, offset only 17.5% of regional gasoline consumption on a gross basis, and substantially less when evaluated on a net basis. Utilization of existing waste biomass sources may ameliorate these effects, but does not obviate the need for dedicated primary feedstock production. Careful scrutiny of environmental trade-offs is necessary before embracing aggressive ethanol production mandates.

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

Received 17 September 2008 and accepted 18 November 2008

Introduction

Interrelated concerns about increasing oil prices, national security, and global climate change are driving large-scale efforts to implement sustainable energy alternatives. Biofuels are widely viewed as a leading alternative to fossil energy, and in recent years favorable government policies have promoted rapid increases in US biofuel production, particularly corn ethanol. Such growth trends are forecast to continue, as renewable fuels standards (RFS) in the Energy Independence and Security Act (EISA) of 2007 mandate the production of 136 billion L of biofuel, including 83 billion L derived from noncorn feedstocks, by 2022 (Sissine, 2007). This goal amounts to well over five times the 24.6 billion L of ethanol produced in 2007.

As biofuel production targets have grown, concerns about social and environmental consequences of large-scale production have also become increasingly prominent. Although most recent life cycle analyses show a positive net energy benefit (NEB) from US corn ethanol and other commercialized biofuel processes when all fossil fuel inputs are taken into account (Shapouri *et al*., 2002; Dias de Oliveira *et al*., 2005; Hill *et al*., 2006;

Correspondence: Matthew J. Cohen, e-mail: mjc@ufl.edu

Schmer *et al*., 2008), significant concerns have been raised by studies that report negative NEBs from US corn ethanol and major cellulosic feedstock alternatives (Giampietro & Ulgiati, 2005; Pimentel & Patzek, 2005, 2007). Further, the stated environmental benefits of biofuels have been questioned by studies indicating that land use changes necessary for large-scale feedstock cultivation may exacerbate soil erosion, forest loss, and greenhouse gas emissions at globally significant levels (Giampietro & Ulgiati;Fargione *et al*., 2008; [39], 2005 [14]Searchinger *et al*., 2008). Increasing competition between food and fuel markets has also become an economic and geopolitical concern, particularly in light of global food cost inflation, local grain shortages, and food riots observed in 2008. Such criticisms have prompted calls for implementation of biofuel feedstocks that are decoupled from food production and that minimize environmental impacts on a life cycle basis (Perlack, 2005; Hill *et al*., 2006; Kim & Hayes, 2006; Tilman *et al*., 2006; Schmer *et al*., 2008).

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

In this study we compare energy balances and water resource impacts for four potential ethanol feedstocks – corn, sugarcane, sweet sorghum, and southern pine (i.e., plantations of *Pinus elliottii*, slash pine or *Pinus taeda*, loblolly pine) – for two southeastern states, Florida and Georgia. Although neither state is currently a major biofuel producer, both have warm, wet climates that support high primary productivity. Many analysts therefore forecast a rapid expansion of biofuel production in these and other southeastern states as national production mandates take effect (Kim & Hayes, 2006), and several new ethanol production facilities that use one or more of the feedstocks we analyze are currently under consideration or active construction in these states. Additional attention has also been paid to ethanol derived from perennial grasses (e.g., switchgrass), but insufficient data were available for compiling a life-cycle analysis for such crops in the southeast region.

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

Methods

Agricultural inputs (fertilizer, pesticide, herbicide, diesel, machinery, irrigation, seed, labor), feedstock outputs, transportation inputs (fossil fuel and machinery), ethanol conversion inputs (fossil fuel, chemicals, and machinery), and gross ethanol yields were evaluated using life cycle methods commonly used in the analysis of biofuel production (Giampietro *et al*., 1997; Shapouri *et al*., 2002; Dias de Oliveira *et al*., 2005; Gnansounou *et al*., 2005; Pimentel & Patzek, 2005, 2007; Hill *et al*., 2006; Kim & Hayes, 2006; Wang *et al*., 2007; Macedo *et al*., 2008; Schmer *et al*., 2008). Our life cycle analysis was specific to feedstock production and processing in

Florida and Georgia, extended to include associated water resource impacts.

Inputs and yield data were obtained from published literature on agricultural practices, biofuel manufacturing, and water requirements associated with both feedstock production and ethanol manufacturing (detailed input/output analyses are provided in supporting information Tables S1 and S6). All analyses assumed feedstock yields at the farm gate at the high end of published ranges. For example, optimal corn grain yields (12 600 kg ha^{-1}) in Florida and Georgia (as suggested by Wright *et al*., 2004) are 57% higher than average yields (8050 kg ha^{-1}) reported for the two states in 2007 (USDA, 2008a, b) and 37% higher than yields assumed (9300 kg ha^{-1}) in a recent life cycle analysis of Midwestern corn ethanol (Hill *et al*., 2006). Similarly, maximum sweet sorghum yields of 109 000 kg ha^{-1} fresh weight (32 700 kg ha^{-1} dry weight) (Tew & Cobill, 2006) are more than twice the mean yields assumed in a past study of sweet sorghum ethanol in the southeast US (Rains *et al*., 1993) and a more recent study of sweet sorghum ethanol production in China (Gnansounou *et al*., 2005). Sugarcane yields were based on data from the Everglades Agricultural Area (EAA), which has soils and climate that are much more appropriate for intensive sugarcane production than other areas of Florida and Georgia (Baucum *et al*., 2006). Pine forestry yields are based on wood output reported for high intensity cultivation in the southeast over a 25-year rotation (Johnson *et al*., 2005), thus representing an upper bound of recoverable wood biomass.

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

Energy balance

Energy balance calculations were made per unit area (1 ha area). Agricultural inputs were converted to fossil energy equivalents using conversion factors from a recently published life cycle analysis for corn ethanol (Hill *et al*., 2006). Transportation costs for feedstocks to and ethanol from the production facility were based on transport distances and mean per distance energy consumption (Shapouri *et al*., 2002). Energy costs for feedstock conversions were based on a dry mill process for corn (Hill *et al*., 2006), a whole cane process for sugarcane (Shapouri *et al*., 2002), on-farm juice extraction and juice conversion for sweet sorghum (Grassi *et al*., 2002; Renergie Inc., 2007), and acid pretreatment and staged enzymatic hydrolysis for wood (Kim & Hayes, 2006; STCI, 2006). The life-cycle NEBR was determined by dividing gross ethanol output in energy units per hectare by the fossil fuel equivalent input requirements. When determining the gasoline displacement of ethanol produced on a net energy basis, we used the life-cycle energy costs of gasoline where each unit of energy delivered required 0.2 energy units to extract, refine, and transport the fossil fuel (Wang *et al*., 2007).

Additional energy output credit was given for marketable coproducts (supporting information Table S5). Corn ethanol is given coproduct credit for dried distiller grain, a high protein animal feed, through a calculation of the fossil energy required to produce alternative feed products (Hill *et al*., 2006). Sugarcane and pine ethanol processes both have a coproduct of exported electricity obtained through combustion of residual biomass (sugarcane bagasse and wood lignin, respectively) in biofuel refineries. This electricity export is credited as the energy equivalent of the natural gas demand displaced within the power grid. The sweet sorghum ethanol process has a coproduct of cellulosic biomass remaining after on-farm juicing, which is then processed into agropellets that can be combusted in a biomass power plant. Similar to the export electricity credit for sugarcane and pine processes, sweet sorghum agropellets are credited for displacing natural gas demand in electricity production. Although natural gas currently comprises only 43% of Florida's electricity production and 9% of Georgia's, we assume natural gas displacement in electricity coproduct calculations due to the fact that peak load capacity increases in the two states have been largely provided by construction of natural gas-fired facilities. NEBR with coproducts for all feedstocks was calculated by adding coproduct energy credits to ethanol output and dividing by energy inputs.

Environmental resource use

For life-cycle assessment of environmental impacts, selection of baseline conditions against which new

  doi: 10.1111/j.1365-2486.2009.01868.x

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

Water resource impacts refer collectively to impacts on human appropriation of freshwater resources and impacts on water quality; by association, and because of the spatially distributed nature of bioenergy production, our life cycle analysis also includes impacts on land resource allocation. Gross land requirements vary by feedstock, annual agronomic productivity and ethanol conversion efficiency (supporting information Table S6). For corn, sweet sorghum, and sugarcane, yields were for an annual harvest cycle. In the case of southern pine, production output for a 25-year rotation was annualized to determine the land area that must be in continuous production to meet ethanol demands. Land requirements for gross yields ($m^2\,GJ_{gross}^{-1}$) were computed directly from estimated biomass yields and conversion efficiency. Land requirements for net energy production ($m^2\,GJ_{net}^{-1}$) were computed by multiplying the land area per gross yield by the [(NEBR)/(NEBR −1)], both with and without coproduct credits (supporting information Table S7).

Water requirements were based upon direct withdrawals for irrigation and ethanol processing (i.e., 'blue' water, or water withdrawn from surface and subsurface stores; Rost *et al*., 2008), and the amount of additional rainfall used for ET during feedstock production as compared with displaced or reference ecosystems (i.e., 'green' water). While direct appropriation of blue water resources to facilitate high feedstock yields is the most obvious use of water, it is increasingly understood that green water use by unirrigated biomass production systems also has critical implications for water resources at a landscape level (Powell *et al*., 2005; Berndes, 2008). The ET rate found in natural pine savanna and low intensity pasture was used as the reference for corn, sweet sorghum, and southern pine feedstocks, while a monotypic sawgrass marsh was used as the reference ecosystem for muck soil sugarcane production. For irrigated feedstocks, blue water use was subtracted from green water use to enumerate ET demand being met through irrigation, rather than rainfall; total water use was the sum of green and blue water. Because irrigation rates for corn and sugarcane exceed estimated green water demand, green water use for these feedstocks was assumed to be zero. Given ethanol yields and crop water use per area (plus comparatively small quantities used in industrial processing), water use for gross ethanol production was determined (Table 1; supporting information Table S6). As with land, the NEBR for each feedstock was used to estimate water resource demands on a net energy basis (supporting information Table S7).

N loading was based on fertilizer application recommendations (as N) to achieve high end yields. Application rates rather than loss rates were used because agronomic N use efficiencies necessary to estimate losses are highly spatially and temporally variable, subject to soil type, climatic conditions, relief, and, in the case of forest operations, stand age. Moreover, existing data on N use (from fertilizer sales) provides a more accurate benchmark against which to compare future loading than does landscape N export in rivers, for which estimates are intrinsically less certain. While fertilizer application rates provide a basis for comparing eutrophication potential from biofuel feedstocks, the results may exaggerate the impacts of N loading from feedstock systems with high N uptake efficiency and/or low mineral N export rates (e.g., southern pine production forests). As with water use, gross ethanol yields, and N loading rates per area provided the basis for determining N requirements for gross production (Table 1; supporting information Table S6), while NEBR values (supporting information Table S5) were used to estimate net energy N loading (supporting information Table S7).

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

Results

Feedstock energy balances

Feedstock input requirements for corn, sugarcane, sweet sorghum and southern pine cultivation in Florida and Georgia (supporting information Tables S1 and S4) differ in both total magnitude and relative importance.

Table 1 Environmental resource implications of feedstock production to meet the energy equivalent of 13.6 billion L EtOH* production in Florida and Georgia on a gross ($Gross_{EtOH}$) and net energy basis (Net_{Total}; this refers to total energy output, including coproduct 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 ($\times 10^6$ 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 ($\times 10^6$ m^3)‡	–	–	–	–	1810	2470	11 800	14 800
Green water (% 2000 use)**	–	–	–	–	9.1	12.5	59.4	75.3
Blue water ($\times 10^6$ m^3)‡	13 400	43 520	14 040	21 715	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 ($\times 10^6$ m^3)‡	13 400	43 520	14 040	21 715	6460	8840	11 930	14 970
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

*_Biofuels allocation_: Assumed 2022 RFS allocation for Florida and Georgia is 13.6 billion L EtOH, as these states accounted for approximately 10% of total US gasoline consumption in 2006 (EIA, 2008).
†Scale-up for sugarcane reflects an EAA fertilization rate of 40 kg N ha^{-1} on the first 162 000 ha of production and 200 kg N ha^{-1} for other required land area. Likewise, lime inputs increase from 200 to 1000 kg ha^{-1} on non-EAA lands. Assuming that yields and other inputs remain constant, associated $NEBR_{Total}$ for non-EAA production that reflects these higher inputs is 2 : 13 : 1 (supporting information Table S9). Weighted $NEBR_{Total}$for sugarcane in scale-up scenario is thus 2.15 : 1.
‡_Resource scaling_: Gross values for land area scaled up from ha/1000 L EtOH reported in supporting information Table S6 to ha/ 1.36×10^{10} L EtOH. As 1.36×10^{10} L EtOH = 2.9×10^8 GJ, net bioenergy values scaled up from m^2 net GJ^{-1} reported in Table S8. Similar scale up calculations performed for nitrogen, blue water, green water, and total water using gross yield values in supporting information Table S6 and net yield values in supporting information Table S7.
§_% Total land area_: Land area in Florida and Georgia is 2.9×10^7 ha.
¶_% Total forest area_: Baseline forestry area of 16.3×10^6 ha in Florida and Georgia (Bugwood Network, 2002; [8]Carter & Jokela, 2002).
‖_% Nitrogen application_: Total nitrogen applications for Florida and Georgia in 2002 are estimated at 5.9×10^8 kg N based on national fertilizer use (12.0×10^9 kg as N) from the US Economic Research Service (http://www.ers.usda.gov/Data/FertilizerUse) and national and state fertilizer expenditures (US – \$9.75 billion, Florida – \$289 million, Georgia – \$190 million) from the 2002 US Agricultural Census. (http://www.agcensus.usda.gov/Publications/2002/index.asp)
**_% Water use_: Total annual freshwater withdrawals reported at 1.98×10^{10} m^3 for Florida and Georgia in 2000 (Hutson _et al_., 2004).
††_% Gasoline replacement_: For all feedstocks, gasoline replacement % in terms of $Gross_{EtOH} = (1.36^{10}$ L EtOH $\times$ 21.3 MJ L^{-1} EtOH)/ (5.15^{10} L Gas $\times$ 32 MJ L^{-1} Gas). Gasoline replacement % in terms of $Net_{Total} = (1.36^{10}$ L EtOH $\times$ 21.3 MJ L EtOH)/(5.15^{10} L Gas $\times$ 32 MJ L Gas) $\times$ [($NEBR^{-1}_{Total}$)/$NEBR_{Total}$) $\times$ ($EROEI_{Gasoline}$/($EROEI^{-1}_{Gasoline}$)], where $EROEI_{Gasoline}$ (i.e., energy return on energy invested for gasoline) is assumed at 5 : 1 (Wang _et al_., 2007).
NEBR, net energy benefit ratio; EAA, Everglades Agricultural Area.

Total energy inputs at the farmgate – that is, postharvest, but pretransport – are 7.47, 4.97, 7.33, and 2.03 MJ L^{-1} of overall ethanol yield, respectively. Direct combustion of fossil fuels, primarily as diesel, represents the largest feedstock energy input for pine, sugarcane, and sweet sorghum; N fertilizer is the largest input for corn production. Feedstock production inputs range from 24% of total life cycle energy costs for pine, 36% for corn, 44% for sweet sorghum, to a high of 57% for sugarcane (Fig. 1).

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

At 12 MJ L^{-1} EtOH, dry mill conversion of corn kernels is the most fossil energy intensive ethanol production process considered. Fossil energy costs for conversion of other feedstocks were 6 MJ L^{-1} EtOH for sweet sorghum, 5 MJ L^{-1} for pine wood chips, and 0.28 MJ L^{-1} for sugarcane (supporting information

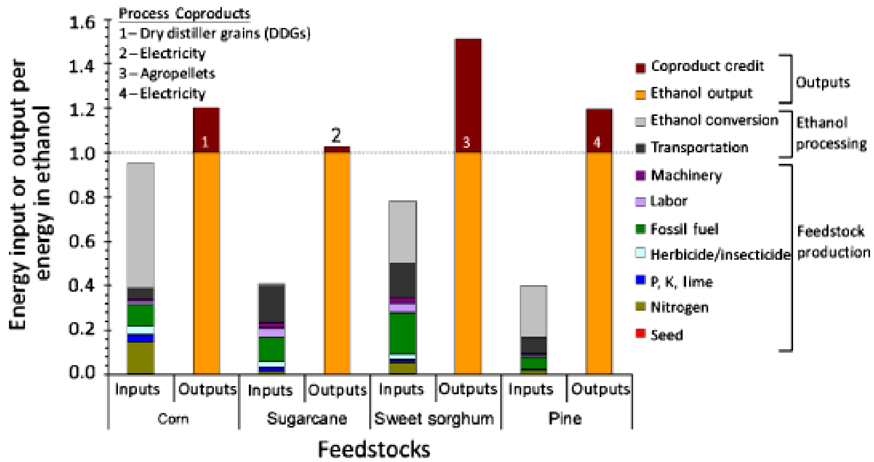

Fig. 1 Energy inputs and outputs for ethanol production from four feedstocks. Inputs are partitioned into feedstock requirements and processing/transportation. Outputs are partitioned into ethanol yield and coproducts production. All input and output flows are scaled by the energy in ethanol (MJ/MJ).

Table S5). Power provided from combustion of nonfermentable feedstock biomass at the ethanol facility significantly reduces fossil energy needs for both wood and sugarcane processes.

The sum of agricultural inputs, postharvest transport, and ethanol conversion in comparison with gross ethanol yields (Fig. 1, supporting information Table S5) suggests that all four feedstocks generate net energy (i.e., NEBR > 1.0) on a fossil fuel equivalent basis, even neglecting coproducts. Southern pine had the highest NEBR with values near 3 (2.97 : 1) for ethanol production with an electricity coproduct and 2.49 : 1 for ethanol without coproduct credit. Sugarcane and sweet sorghum NEBRs were 2.51 and 1.94 : 1, respectively, with inclusion of coproduct credits. Sugarcane maintains a relatively high NEBR of 2.44 : 1 when coproducts are not considered, but sweet sorghum falls significantly (1.28 : 1). Corn, which had an NEBR of 1.26 : 1 after coproduct credit for dried distiller grains and only 1.05 : 1 when excluding coproducts, is clearly the most energy intensive of the four feedstocks.

Feedstock water resource demands

Land, N, and water requirements for gross ethanol and net energy production vary among feedstocks (Fig. 2; supporting information Tables S6 and S7). Southeastern corn had the highest gross and net resource demand for most categories; total water demands for net energy production are approximately an order of magnitude higher than for other feedstocks (Fig. 3). Both sugarcane and sweet sorghum, crops with high productivity and ethanol conversion efficiency, are notable for relatively low land demands on a gross and net yield basis.

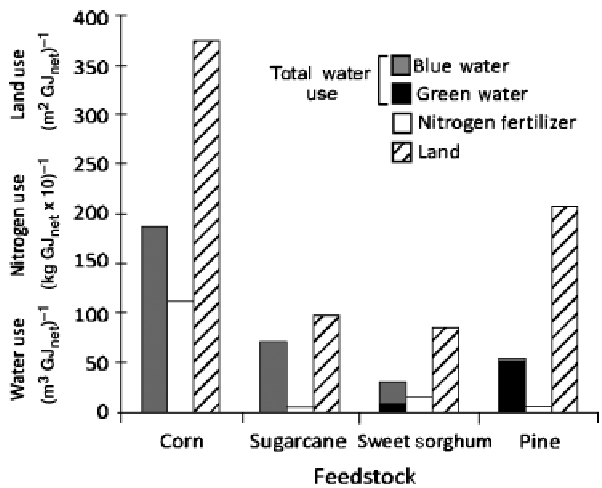

Fig. 2 Water, nitrogen, and land use requirements per net energy production for four Southeastern feedstocks. Values are reported after including credits for coproducts.

Because much of the net energy yield for sweet sorghum is from coproduct credit, water demands for sweet sorghum when considering only the net energy return from ethanol are higher than either sugarcane or pine (Fig. 3). While N fertilizer demands are low for sugarcane in the EAA, expansion of sugarcane production into areas with nonpeat soils would require significantly higher N fertilization rates (Table 1; supporting information Table S9). Pine feedstocks have low N and negligible blue water demand, but high land use and green water requirements in relation to other feedstocks on a gross yield basis. Total water required for pine ethanol is less than other feedstocks when considered on a net energy basis (Fig. 3).

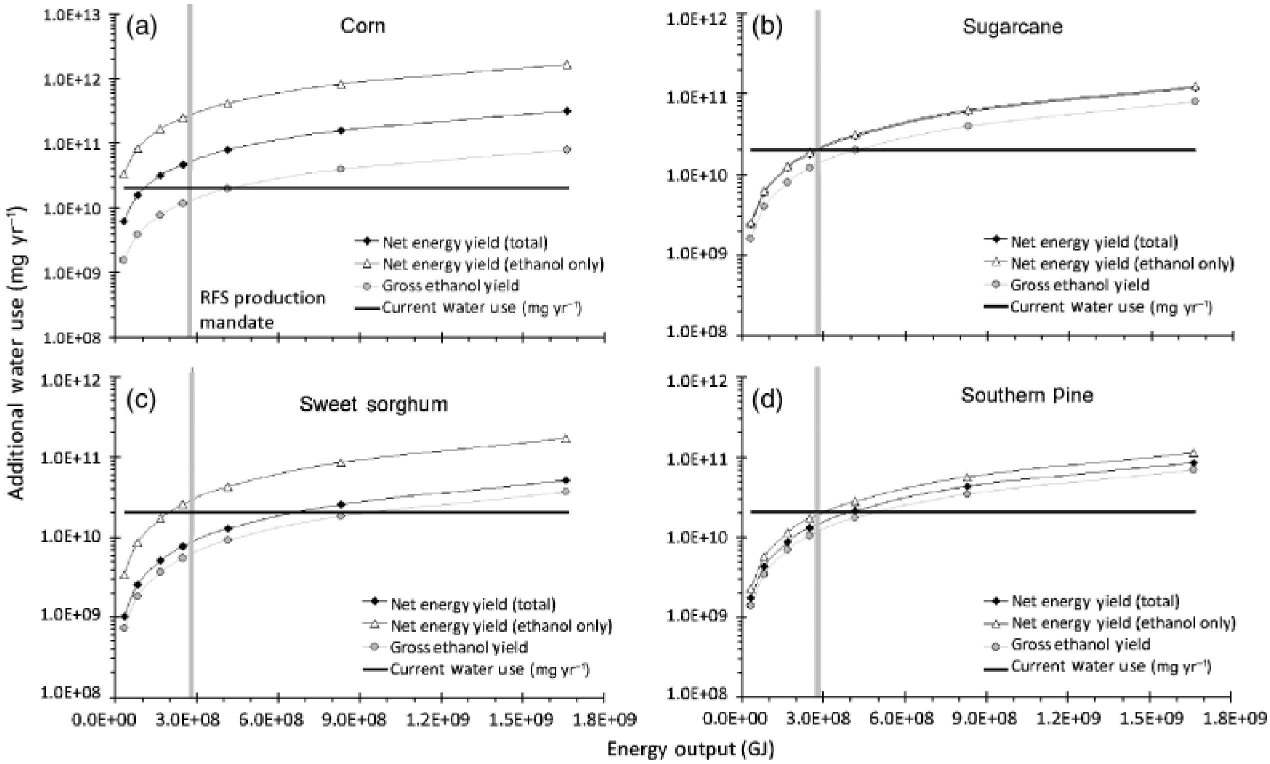

Fig. 3 Projected water use ($Mg\,yr^{-1}$) as a function of energy yield from (a) corn, (b) sugarcane, (c) sweet sorghum and (d) southern pine ethanol. Lines represent water use per gross energy yield (gross), per net energy yield with coproducts (ethanol only), and per net energy yield without coproduct credits (total). Points along each line correspond to replacement of 2%, 5%, 10%, 15%, 25%, 50%, and 100% of current gasoline use. Current freshwater water use is shown with a horizontal black line. A vertical grey line depicts the energy equivalent of 2022 RFS ethanol mandates (13.6 billion L; 2.90E + 08 GJ).

Water resource implications of RFS: 2022

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

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

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

N fertilizer use associated with feedstock production sufficient to meet RFS targets would be most dramatic for corn, which would necessitate additional N loading

  doi: 10.1111/j.1365-2486.2009.01868.x

to the landscape of nearly 1.5 times the application rates for all land uses during 2000. N demands for sweet sorghum and sugarcane (the latter adjusted to agronomic requirements outside the EAA) are significantly less than corn, but N loading for either crop exceeds 60% of total N use in the region in 2000. N requirements for pine feedstock production are relatively small in comparison to crop feedstocks, but would still require a 16% increase in total N use vis-á-vis use in 2000.

Water resource costs for fossil energy replacement

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

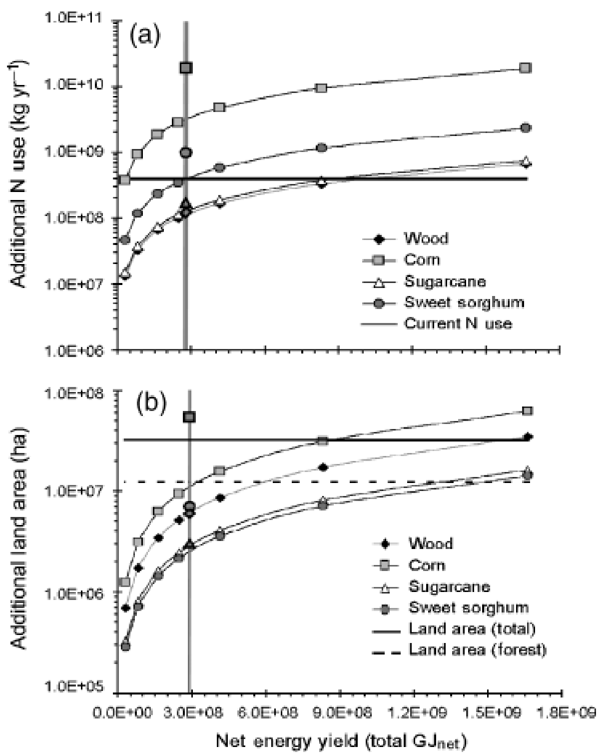

Fig. 4 Projected use of (a) N, and (b) land under various gasoline offset scenarios, based on total net energy production (including coproducts) for four candidate feedstocks. Points along each line correspond to 2%, 5%, 10%, 15%, 25%, 50%, and 100% of current gasoline use. Current resource use (for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

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

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 yr^{-1} 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 L dry ton^{-1}, 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 (supporting information Table S8).

Sensitivity analysis

Life cycle metric sensitivity to input and process assumptions is substantial (supporting information Table S9). 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 (0.4–2.3 and 1.4–2.7 $kg\,N\,GJ_{net}^{-1}$, respectively), but had significantly less effect on NEBR, water use, and land use ($\sim$ 15% change). Similarly, while decreasing transportation costs by a factor of 5 for both sugarcane and sweet sorghum increased NEBR dramatically ($\sim$ 25–40% increase), the effect on water, land and N use was far less significant ($\sim$ 10% decrease). The key input assumption for pine was the addition of enzymes to convert celluloses to fermentable sugars; the published range of inputs is 0.04–0.81 $kg\,L^{-1}$ EtOH (STCI, 2006), from which we assumed 0.22 $kg\,L^{-1}$ for the baseline scenario. The effect of this is dramatic, with NEBR varying between 1.96 and 5.14 in response to that range, and water use per net energy decreasing by a $>$40% at low levels of enzyme use. Increases in the gross ethanol conversion rate result in somewhat higher NEBRs, but the associated increases in ethanol output per hectare lead to far more significant implications in terms of reducing overall land, water, and N demands. Such effects are particularly pronounced for the pine ethanol process, as large reductions in environmental life cycle demands occur when conversion efficiency is increased from the base case of 0.257 L EtOH kg^{-1} to a technically plausible 0.30 L EtOH kg^{-1}.

Discussion

Meeting the RFS mandates with primary feedstocks will engender important environmental trade-offs. While our results suggest major differences between feedstocks regarding water resource impacts, net fossil energy displacement potential, and scale-up feasibility, it is also apparent that biofuel production in Florida and Georgia from any of the four feedstocks considered would have significant impacts on both land use and water resources when scaled up to RFS levels of gross production. It is also clear that the impacts accrue principally from feedstock production rather than from fermentation and distillation; for example, water use in a modern distillery ($\sim$ 10 L water L^{-1} EtOH) is just over 1% of the total life-cycle water use estimated for pine ethanol production. Moreover, it is likely that actual land use and water resource impacts of feedstock production may be somewhat higher than our results suggest, mainly due to our use of generous assumptions regarding agronomic output potential. Additional environmental impacts from P loading, soil erosion and/or oxidation, and loss of wildlife habitat – while not explicitly considered in this analysis – are also implied by increased biofuel feedstock production. All these potential impacts should be considered when comparing relative costs and benefits of different candidate feedstocks and in developing policy to manage water supply and pollutant-load demands that will accompany large-scale production.

Corn currently dominates US ethanol production. Although most recent studies show a positive, but generally small, NEBR from corn ethanol, there is growing concern about negative externalities of increased corn ethanol production, including high N and pesticide loading, upward pressure on grain prices, and rapid conversion of lands previously held in the CRP (Pimentel & Patzek, 2005; Hill *et al*., 2006; Tilman *et al*., 2006; NRC, 2007; Donner & Kucharik, 2008; Fargione *et al*., 2008; Searchinger *et al*., 2008). In the southeast, our study suggests that corn is notable for high blue water and N fertilizer requirements and low NEBR compared with other feedstocks, even under the assumption of very high optimum corn yields. A sensitivity analysis using yield of 7875 $kg\,ha^{-1}$, which is a more plausible average corn yield for the southeast than the optimum number we use in our base case, gives an NEBR with coproduct of only 1.03 (supporting information Table S9). Given consistently low NEBR values, high environmental resource requirements, and limited future potential for increasing biofuel process efficiency, corn represents the least desirable option for large-scale ethanol production in the southeast.

Sugarcane is the primary feedstock for ethanol production in Brazil, the world's second largest ethanol producer. Our estimated NEBR of 2.51 for sugarcane ethanol corroborates numerous studies that suggest sugarcane ethanol conversion is more efficient than corn ethanol (Dias de Oliveira *et al*., 2005; Hill *et al*., 2006; Macedo *et al*., 2008). This result is significantly higher than the NEBRs reported in a recent analysis of sugarcane ethanol in Louisiana and Brazil (Pimentel & Patzek, 2007), but lower than the NEBR values of 3.7 : 1 (Dias de Oliveira *et al*., 2005) and 9.3 : 1 (Macedo *et al*., 2008) reported in two recent studies of Brazilian sugarcane ethanol. Discrepancies among these studies are principally explained by differences in energy intensity of reported agricultural inputs and transportation efficiency. Estimates of agricultural inputs for Brazilian sugarcane range from a low of 10.8 $GJ\,ha^{-1}$ (Macedo *et al*., 2008) to a high value of 35.8 GJ ha^{-1} (Dias de Oliveira *et al*., 2005). Because Brazil is generally considered to be among the world's most efficient producers of sugarcane (Bolling & Suarez, 2001), it is not surprising that our estimate of agricultural energy inputs into Florida sugarcane (38.3 GJ ha^{-1} – supporting information Table S2) is somewhat higher than those reported for Brazil. Differences between the sugarcane agriculture energy inputs in our study and the 56.1 GJ ha^{-1} of agricultural inputs reported by Pimentel & Patzek (2007) for Louisiana sugarcane are largely explained by the much lower N fertilizer requirements in the organic soils of the EAA (40 kg ha^{-1} in the EAA vs. 196 kg ha^{-1} in Louisiana). Our transportation energy cost of 0.25 MJ kg^{-1} for sugarcane biomass (and all other feedstocks) is based on biomass transport distance data for existing US corn ethanol manufacturing facilities (Shapouri & Salassi, 2006). The resultant energy cost for transporting Florida sugarcane using this method is five times greater than the cost (0.05 MJ kg^{-1}) reported by Macedo *et al*. (2008) for Brazilian sugarcane ethanol, but one half the transport energy cost (0.5 MJ kg^{-1}) reported by Pimentel & Patzek (2007) for both Brazilian and Louisiana sugarcane ethanol. Given that the location of ethanol plants and, by extension, the crop hauling distance for feedstocks in Florida and Georgia is unknown at this time, we believe that the most straightforward comparison of feedstocks is provided by the standardized mass-based transportation energy cost that we use. NEBR for Florida sugarcane ethanol does increase significantly to 3.49 : 1 if transport energy costs for sugarcane are reduced to the level suggested by Macedo *et al*. (2008), thereby reducing the land area requirements from 98 to 83 $m^2\,GJ_{net}^{-1}$ and total water use from 72 to 61 $m^3\,GJ_{net}^{-1}$ (supporting information Table S9).

Despite consensus that the NEBR from sugarcane is significantly higher than from corn, use of the existing Florida sugarcane crop as a dedicated ethanol feedstock has been generally regarded as uneconomical, mostly due to government price supports that inflate the price of US sugar relative to the world market (Shapouri & Salassi, 2006). It is also relevant that the biofuel potential of existing Florida sugarcane is small: allocation of all existing sugarcane production in the EAA (162 000 ha) to ethanol would produce only 1.25 billion L EtOH yr^{-1}, approximately 11% of the 2022 RFS allocation for Florida and Georgia, and $<2\%$ of current gasoline consumption. Moreover, costs of mitigating downstream P loading to the Everglades and ongoing peat soil oxidation in the EAA are two additional challenges to using sugarcane as a bioenergy crop in south Florida. Regional scale-up scenarios for sugarcane, which already show high water use, are optimistically based on EAA crop yields. Large-scale sugarcane production in Florida and Georgia outside the EAA certainly requires larger fertilization inputs and, although insufficient data are available for an independent life cycle analysis of non-EAA sugarcane, is also likely to have lower productivity and NEBR values than those shown in our sensitivity analyses (supporting information Table S9).

Sweet sorghum is widely viewed as a promising feedstock due to low fertilizer and water requirements compared with corn and sugarcane. Our results support this contention; sweet sorghum exhibits high productivity, low land use requirements, and, by extension, low total water requirements in comparison to other feedstocks. Although total ET is similar to corn ($\sim$ 700 mm over 120 days), blue water requirements for sweet sorghum are lower (250 vs. 500 mm) because, unlike corn, transient wilting stress can be tolerated without adverse effects on yield (Steduto *et al*., 1997). As such, irrigation schedules for sweet sorghum can be reactive to dry conditions, rather than precautionary, as is generally necessary with corn in the southeast US (Wright *et al*., 2004). Large quantities of fossil energy in the sweet sorghum process are diesel fuel for harvest, juicing, and juice transportation. As such, increased machine efficiency and minimization of transport distances offer the clearest opportunities for boosting NEBR values.

However, important unanswered questions remain for sweet sorghum ethanol. Like other feedstocks, estimates of land requirements for sweet sorghum are based on scaling up optimal yields of 32.7 dry tons ha^{-1} (Tew & Cobill, 2006) that are unlikely to be achieved on a consistent basis across sites. Furthermore, it seems unlikely that relatively low published N fertilization rates of 160 kg ha^{-1} (Mylavarapu *et al*., 2007) are sustainable given a harvest process that utilizes all above ground biomass for biofuel production (i.e., ethanol plus agropellets). Assuming optimal sweet sorghum yields, N loss rates from harvest are 300–330 kg ha^{-1} (Soileau & Bradford, 1985; Barbanti *et al*., 2006), twice the suggested fertilization rate, even without taking into account N losses due to volatization and leaching. While a higher N fertilization rate only slightly lowers the NEBR value of the biofuel process from 1.94 : 1 to 1.83 : 1, N loadings to the environment for biofuel return almost double from 1.4 to 2.7 kg N net GJ^{-1} (supporting information Table S9). In short, NEBR and environmental resource use estimates for sweet sorghum must be considered provisional until full-scale production examples are evaluated.

Development of ethanol from cellulosic feedstocks, such as wood and fibrous grasses, which can be grown on lands not suitable for large-scale food production is a clear priority for economical and environmentally sustainable production. The EISA contains provisions to encourage US cellulosic ethanol production beginning in 2012, and a number of facilities using cellulosic feedstocks such as switchgrass, wood, and agricultural residues are currently under construction or in preconstruction planning throughout the United States One facility based on conversion of pine wood to ethanol is under construction in southern Georgia and, if opened on schedule in 2008, will be the first commercially operational cellulosic ethanol plant in the United States.

The NEBR for pine-based ethanol (2.97 : 1) is highest of the four feedstocks. This result contrasts sharply with the 59% net energy loss for a wood to ethanol process as reported by Pimentel & Patzek (2005). This discrepancy is largely attributable to the inclusion of electricity and steam as exogenous inputs to the ethanol production process in the Pimentel & Patzek (2005) study, while our analysis assumes cellulosic ethanol facilities designed to utilize residual lignin combustion for supplying all power needs in the facility and to yield excess electricity as a coproduct export (Kim & Hayes, 2006; STCI, 2006; Schmer *et al.*, 2008). At the same time, several other recent studies of cellulosic feedstock such as switchgrass (Schmer *et al.*, 2008) and low intensity prairie grasses (Tilman *et al.*, 2006) show significantly NEBRs higher than we report for southern pine. This difference is attributed to our inclusion of the energetic costs of cellulase enzymes in the conversion process (STCI, 2006) – a cost that it is not explicitly included by most other studies (Tilman *et al.*, 2006; Schmer *et al.*, 2008). Our base case assumption of the enzyme mass required per liter of ethanol produced ($0.22\,kg\,L^{-1}$) from woody biomass is relatively conservative, as recent estimates range from 0.04 to $0.81\,kg\,L^{-1}$ (STCI, 2006). Although a lowering of enzyme application rate from 0.22 to $0.04\,kg\,L^{-1}$ dramatically raises the NEBR to 5.14 : 1, corresponding reductions in land ($209–173\,m^2\,GJ_{net}^{-1}$, and associated water use from ($51–43\,m^3\,GJ_{net}^{-1}$) are relatively small. By contrast, changing the assumed gross conversion efficiency from $0.257\,L\,EtOH\,kg^{-1}$ biomass to $0.30\,L\,EtOH\,kg^{-1}$ biomass while still using the base case level of enzyme has the effect of reducing the land footprint from 209 to $175\,m^2\,GJ_{net}^{-1}$ and associated water use from 51 to $43\,m^3\,GJ_{net}^{-1}$. That is, an approximate doubling of the NEBR by assuming no energy cost for enzymes has approximately the same effect on land and water use as increasing the gross ethanol conversion efficiency by 20%. We infer that overemphasizing the NEBR could lead to suboptimal decisions about feedstocks and production processes; indeed, where the NEBR is larger than 2, increases of gross yield progressively become much more important than net energy yield in terms of reducing environmental impact metrics from feedstock production.

A distinct disadvantage of pine feedstock is comparatively low agronomic productivity per unit area and high associated green water demands for large-scale production. Given existing economic utilization of pine forest products in the southeast, additional demand for cellulose associated with large-scale ethanol production is likely to place production pressure on remaining natural forest lands – which may be viewed as both a source of biomass standing crop, and land area that can be converted into high intensity forestry. While impacts of green water consumption may not be as immediately apparent as direct blue water withdrawals, it is clear that increased cover of high intensity plantation forestry can significantly lower regional water tables, reduce stream flows, and, by extension, potentially affect water supplies and aquatic ecosystem function (Jackson *et al.*, 2005; Powell *et al.*, 2005); estimates of stream flow reduction following afforestation are roughly $250\,mm\,yr^{-1}$, which is the excess ET value we attribute to high intensity pine (Powell *et al.*, 2005).

It is also clear from these results that a significant fraction of the biomass necessary to achieve RFS mandates will need to be met with dedicated feedstocks. While waste biomass can reasonably be used for some production, significant economic and energetic costs associated with the concentration and transportation of diffuse biomass sources currently – and perhaps inherently – limit large-scale use of waste biomass for ethanol production (Gallagher *et al.*, 2003; Perlack, 2005). Moreover, estimated gross yields (equivalent to 50% of RFS mandates) will be markedly reduced if evaluated on a net energy basis. Other potential uses for waste biomass sources, including combustion for electrical power generation, are gaining momentum and may reduce available supply for ethanol (Perlack, 2005). Finally, though waste biomass is often regarded as a free source of energy, appropriation of crop and forestry residues for biofuels implies that such residues will no longer be returned to crop and forestry lands, meaning that nutrients or organic matter previously recycled through these sources must be replaced (presumably through fossil fuel-based processes) if soil productivity and hydraulic properties are to be maintained (Varvel *et al.*, 2008). Taken together, these issues suggest that dedicated feedstock production will be required to provide most of the biomass needed to fulfill RFS production goals and, by extension, that future water resource impacts can be justifiably estimated from land use changes required for this additional dedicated production.

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

While this work adds to the growing list of life-cycle studies contending that biomass-to-ethanol processes can yield net energy, the associated water resource implications suggest a need to explicitly consider environmental trade-offs associated with extensive feedstock production. All feedstocks, when produced at levels required to meet RFS volumetric production goals, will contribute substantially to water and land use challenges already facing the southeast. These challenges are amplified when resource impacts are considered on a net energy basis, which provides a more realistic assessment of fossil energy replacement than gross energy production. While it is not possible in this context to adequately enumerate trade-offs between additional water resource stresses on one hand and the compelling needs to limit fossil energy dependence on the other, it is essential that bioenergy policy discussions explicitly recognize the strong potential for conflicting priorities, and adequately plan to balance them.

References

Barbanti L, Grandi S, Vecchi A, Venturi G (2006) Sweet and fibre sorghum (*Sorghum bicolor* (L.) Moench), energy crops in the frame of environmental protection from excessive nitrogen loads. *European Journal of Agronomy*, **25**, 30–39.

Baucum LE, Rice RW, Schueneman TJ (2006) *An Overview of Florida Sugarcane*. IFAS Publication Number SS-AGR-232, University of Florida, Gainesville.

Berndes G (2008) Future biomass energy supply: the consumptive water use perspective. *International Journal of Water Resources Development*, **24**, 235–245.

Bolling C, Suarez NR (2001) *The Brazilian sugar industry: recent developments*. Sugar and Sweetener Situation and Outlook SSS-232, Market and Trade Economics Division, Economic Research Service, United States Department of Agriculture, pp. 14–18

Bugwood Network (2002) *Forests and Timberland*. College of Agricultural and Environmental Sciences, University of Georgia, Athens. http://www.bugwood.org/intensive/forests_and_timberland.html, accessed September 9, 2008.

Carpenter SR, Caraco NF, Corell DL, Howarth RW, Sharpley AN, Smith VH (1998) Nonpoint Pollution of Surface Waters with Phosphorus and Nitrogen. *Ecological Applications*, **8**, 559–568.

Carter DR, Jokela EJ (2002) *Florida's Renewable Forest Resources*. IFAS Publication Number CIR-143, University of Florida, Gainesville.

Code of Federal Regulations (2008) *Title 40: protection of environment; part 130 – water quality planning and management*. http://ecfr.gpoaccess.gov/cgi/t/text/text-idx?c=ecfr&tpl=/ecfrbrowse/Title40/40cfr130_main_02.tpl, accessed September 9, 2008.

Cohen MJ, Lamsal S, Korhnak L, Long L (2008) *Spatial Nutrient Loading and Sources of Phosphorus in the Newnans Lake Watershed*. St Johns River Water Management District Special Report # SJ2008-SP29, Palatka FL.

Dias De Oliveira ME, Vaughn BE, Rykiel EJ (2005) Ethanol as fuel: energy, carbon dioxide balances, and ecological footprint. *Bioscience*, **55**, 593–602.

Donner SD, Kucharik CJ (2008) Corn-based ethanol production compromises goal of reducing nitrogen export by the Mississippi River. *Proceedings of the National Academy of Sciences*, **105**, 4513–4518.

Energy Information Administration (2008) *State Energy Profiles* (. EIA, Washington, DC, http://tonto.eia.doe.gov/state/, accessed September 9, 2008.

Fargione J, Hill J, Tilman D, Polasky S, Hawthorne P (2008) Land clearing and biofuel carbon debt. *Science*, **319**, 1235–1238.

Florida Statutes (2008) *Chapter 373.042, minimum flows and levels*. http://www.leg.state.fl.us/statutes/index.cfm?App_mode=Display_Statute&URL=Ch0373/ch0373.htm, accessed September 9, 2008.

Gallagher PW, Dikeman M, Fritz J, Wailes E, Gauthier W, Shapouri H (2003) Supply and social cost estimates from crop residues in the United States. *Environmental and Resource Economics*, **24**, 335–358.

Giampietro M, Ulgiati S (2005) Integrated assessment of large-scale biofuel production. *Critical Reviews in Plant Science*, **24**, 365–384.

Giampietro M, Ulgiati S, Pimentel D (1997) Feasibility of large-scale biofuel production. *BioScience*, **47**, 587–600.

Gnansounou E, Dauriat A, Wyman CE (2005) Refining sweet sorghum to ethanol and sugar: economic trade-offs in the context of North China. *Bioresource Technology*, **96**, 985–1002.

Grassi G, Fjallstrom T, Qiong Z (2002) *Large-scale integration of bioenergy with petrochemical complexes*. 12th European Conference on Biomass for Energy, Industry and Climate Protection, 17–21 June, Amsterdam, pp 1386–1390.

Hill J, Nelson E, Tilman D, Polasky S, Tiffany D (2006) Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. *Proceedings of the National Academy of Sciences*, **103**, 11206–11210.

Hutson SS, Berber NL, Kenny JF, Linsey KS, Lumia DS, Maupin MA (2004) *Estimated Use of Water in the United States in 2000*. Circular 1268, United States Geological Survey, Reston, Virginia.

Jackson RB, Jobbagy EG, Avissar R *et al*. (2005) Trading water for carbon with biological carbon sequestration. *Science*, **310**, 1944–1947.

Johnson LR, Lippke B, Marshall JD, Comnick J (2005) Life-cycle impacts of forest resource activities in the Pacific northwest and southeast United States. *Wood and Fiber Science*, **37**, 30–46.

Kim J, Hayes KM (2006) *Southern Pine as Feedstock for Renewable Fuel Industry: A Feasibility Study of Lignocellulose Ethanol Production in Georgia*. Enterprise Innovation Institute, Georgia Institute of Technology, Atlanta.

Macedo IC, Seabra JEA, Silva JEAR (2008) Green house gasses emissions in the production and use of ethanol from sugarcane in Brazil: the 2005/2006 averages and a prediction for 2020. *Biomass and Bioenergy*, **32**, 582–595.

Milbrandt A (2005) *A Geographic Perspective on the Current Biomass Resource Availability in the United States*. NREL/TP-560-39181, National Renewable Energy Laboratory, Golden, CO.

Mylavarapu R, Wright D, Kidder G, Chambliss CG (2007) *UF/IFAS Standardized Fertilization Recommendations for Agronomic Crops*. IFAS Publication Number SL129, University of Florida, Gainesville.

National Research Council (2007) *Water Implications of Biofuels Production in the United States*. National Academies Press, Washington.

Perlack RD (2005) *Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply*. Oak Ridge National Laboratory, Oak Ridge, TN.

Pimentel D, Patzek TW (2005) Ethanol production using corn, switchgrass, and wood; biodiesel production using soybean and sunflower. *Natural Resources Research*, **14**, 65–76.

Pimentel D, Patzek TW (2007) Ethanol production: energy and economic issues related to U.S. and Brazilian sugarcane. *Natural Resources Research*, **16**, 235–242.

Powell TL, Starr G, Clark KL, Martin TA, Gholz HL (2005) Ecosystem and understory water and energy exchange for a mature, naturally regenerated pine flatwoods forest in north Florida. *Canadian Journal of Forest Resources*, **35**, 1568–1579.

Rains GC, Cundiff JS, Welbaum GE (1993) Sweet sorghum for a piedmont ethanol industry. In: *New Crops* (eds Janick J, Simon J), pp. 394–399. Wiley, New York.

Renergie Inc. (2007) *The Comprehensive Development of an Ethanol Industry in the State of Florida Using Sweet Sorghum as Feedstock*. Florida Renewable Energy Technologies Grant Program Application, Florida Department of Environmental Protection, Tallahassee.

Rost S, Gerten D, Bondeau A, Lucht W, Rohwer J, Schaphoff S (2008) Agricultural green and blue water consumption and its influence on the global water system. *Water Resources Research*, **44**, WO09405, doi: 10.1029/2007WR006331.

STCI (S&T Consultants, Inc.). (2006) *Wood to Ethanol and Synthetic Natural Gas Pathways*. Natural Resources Canada, Office of Energy Efficiency, Ottawa.

Schmer MR, Vogel KP, Mitchell RB, Perrin RK (2008) Net energy of cellulosic ethanol from switchgrass. *Proceedings of the National Academy of Sciences*, **105**, 464–469.

Searchinger T, Heimlich R, Houghton RA *et al*. (2008) Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land use changes. *Science*, **319**, 1238–1240.

Shapouri H, Duffield JA, Wang M (2002) *The Energy Balance of Corn Ethanol: An Update*. Agriculture Economic Report No. 814. United States Department of Agriculture, Washington, DC.

Shapouri H, Salassi M (2006) *The Economic Feasibility of Ethanol Production from Sugar in the United States*. United States Department of Agriculture, Washington, DC.

Sissine F (2007) *Energy Independence and Security Act of 2007: A Summary of Major Provisions*. Congressional Research Service, Washington, DC.

Soileau JM, Bradford BN (1985) Biomass and sugar yield response of sweet sorghum to lime and fertilizer. *Agronomy Journal*, **77**, 471–475.

Steduto P, Katerji N, Puertos-Molina H, Unlu M, Mastrorilli M, Rana G (1997) Water-use efficiency of sweet sorghum under water stress conditions: gas-exchange investigations at leaf and canopy scales. *Field Crops Research*, **54**, 221–234.

Tew TL, Cobill RM (2006) Evaluation of sweet sorghum as a complementary bioenergy crop to sugarcane in Louisiana. *Journal of the American Society of Sugar Cane Technologists*, **26**, 57.

Tilman D, Hill J, Lehman C (2006) Carbon-negative biofuels from low-input high-diversity grassland biomass. *Science*, **314**, 1598–1600.

United States Department of Agriculture (2008a) *Field Crops, Corn, County Estimates, Florida, 2007*. National Agricultural Statistics Service, Orlando, FL.

United States Department of Agriculture (2008b) *Georgia County Estimates, Corn, 2006–2007*. National Agricultural Statistics Service, Athens, GA.

Varvel GE, Vogel KP, Mitchell RB, Follett RF, Kimble JM (2008) Comparison of corn and switchgrass on marginal soils for bioenergy. *Biomass and Bioenergy*, **32**, 18–21.

Wang M, Wu M, Huo H (2007) Life-cycle energy and greenhouse gas emission impacts of different corn ethanol plant types. *Environmental Research Letters*, **2**, 024001.

Wright D, Marois J, Rich J, Sprenkel R (2004) *Field Corn Production Guide*. IFAS Publication Number SS-AGR-85, University of Florida, Gainesville, 16 pp.

Supporting Information

Additional Supporting Information may be found in the online version of this article:

Table S1. Farm energy requirements for southeastern corn production.

Table S2. Farm energy requirements for Florida sugarcane production.

Table S3. Estimated farm energy requirements for southeastern sweet sorghum production.

Table S4. Energy requirements for southeastern pine production (25 yr rotation).

Table S5. Energy balances for southeastern ethanol feedstocks (MJ/l).

Table S6. 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.].

Table S7. Comparative inputs for southeastern feedstocks per net GJ of ethanol production (with and without co-product credits).

Table S9. Ethanol potential from existing waste biomass sources.

Table S10. 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).

Please note: Wiley-Blackwell are not responsible for the content or functionality of any supporting materials supplied by the authors. Any queries (other than missing material) should be directed to the corresponding author for the article.