The Water Resource Implications of Large-Scale Bioethanol Production

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…To Get Energy

Among the keystone challenges of the next 50 years – given the coupled problems of climate change, geopolitical instability in oil regions, and projected peak and decline in global oil production – is continuing to meet massive energy requirements of modern society. The problem is daunting: global fossil energy consumption in 2006 was ~390 exajoules (3.9×10^{20} J), nearly half as oil. Annual US liquid fuel use in 2006 exceeded 500 billion liters, 40% of the global total. In Florida, where we focus our attention, annual liquid fuel demand is nearly 30 billion liters, roughly 1650 liters/capita/yr. Infrastructure constraints and dependence on liquid fuels make energy replacement challenges particularly pressing for the transportation sector. Whereas electricity from fossil sources can at-least plausibly be replaced with a portfolio of alternatives (wind, nuclear, solar), the contemporary automobile fleet and built US infrastructure necessitate gasoline alternatives, at least in the short term. Bioethanol is one such alternative that has been widely proposed.

The Energy Independence and Security Act (EISA) of 2007 mandates annual biofuel production of 136 billion L by 2022, most of which is likely to be ethanol. Offsetting even this modest fraction of national demand (ca. 18%, after adjusting for ethanol's lower energy content compared to gasoline) from alternative sources presents logistical and technical challenges, including decentralization of production, distribution and storage (ethanol is corrosive), and methods to extract fermentable sugars from cellulosic – and therefore non-food – crops. Moreover, while no consensus can be assumed from recent literature, there are numerous social and environmental reasons to proceed cautiously into aggressive bioenergy policies. Impacts on food and commodity markets, considerations of actual reductions in greenhouse gas emissions (e.g., Searchinger et al. 2008), and indeed the ability to yield energy after input requirements are considered (i.e., net energy) have been vigorously debated recently.

Despite such scrutiny, relatively little is written about water resource impacts of large-scale bioethanol production. Some key forward-thinking exceptions (Giampietro et al. 1997, Berndes 2002) exist; however, for reasons related to modern process details and explicit consideration of life-cycle energy costs, this remains a knowledge gap. Key questions that need answers are: Given energy requirements to grow, harvest, transport, ferment, distill and distribute ethanol, does the process yield net energy? How does this vary by feedstock? How much additional water, directly and indirectly, will be required? How much nitrogen? How much land? Recognizing these unknowns, the National Research Council (2007) issued general report warning that biofuel-driven expansion of agricultural feedstock production into lands requiring supplemental irrigation may increase already unsustainable exploitation of regional water resources. That report argues that a life-cycle approach (net-energy) is essential.

Following the proposed logic of evaluating environmental consequences of large-scale bioethanol production using a life-cycle perspective, we present numbers from recent analyses of four proposed feedstocks in Florida: corn, sugarcane, sweet sorghum and southern pine. Particular production and conversion data and methods are beyond the scope here, but can be obtained from the authors upon request.

It Takes Energy…To Get Energy

The debate over alternatives to fossil energy is long and tortuous. Among the sources of confusion is the distinction between gross and net energy. Gross energy measures energy contained within a particular fuel (including electricity). Net energy, by contrast, represents the difference between gross energy and energy invested from outside the production process. For example, the gross energy content of gasoline is 32 MJ/liter, a constant, barring minor effects of fuel additives. The net energy, however, is dependent on energy requirements to produce and deliver that liter to consumers. If we assume that 7 MJ are expended to get the liter of gasoline into an automobile, the net energy would be 25 MJ – the difference between energy output (32 MJ) and input (7 MJ).

The importance of this distinction is that an energy <u>source</u> requires more energy be yielded than is mobilized to acquire it. A common metric for evaluating energy sources is energy return on energy invested (EROEI), or the ratio output-to-input. EROEI values over 1 are required for a source of energy to be viable, while EROEI less than 1 indicates “sources” that are actually sinks. An important, although not always determinative, factor when comparing energy source feasibility is that higher EROEI processes yield more usable energy per unit of energy invested than lower EROEI processes.

The life cycle of bioethanol from farm to gas pump include significant amounts of fossil fuel energy expended. Agricultural production of feedstocks requires large amounts of diesel, fertilizer, pesticides, electricity, and machinery. Diesel and electricity are frequently used to pre-process and transport harvested feedstocks to ethanol facilities, where fermentation and distillation requires additional inputs of electricity, chemical reagents, and machinery. Finally, diesel and machinery are required to transport ethanol to the pump.

Computation of EROEI for a particular ethanol production process is essentially comparison of total energy inputs (Figure 1), in myriad forms necessary for production but excluding free environmental flows (e.g., sunlight), with energy outputs (ethanol contains 21.3 MJ/liter). The recent literature is replete with such calculations for ethanol from corn, sugarcane, and cellulosic feedstocks (e.g., switchgrass and other “low intensity” graminoid feedstocks). Although substantial disagreement remains, it appears likely that EROEI values for corn ethanol are positive, but low (~1.25:1; Hill et al. 2006), whereas values for sugarcane ethanol are higher (~ 3.4:1 in Brazil; Dias de Oliveira et al. 2005). The prospect of cellulosic ethanol has obvious appeal given that corn and sugarcane are food; recent pilot-scale studies report impressive

EROEI for ethanol from switchgrass and other high cellulose-content grasses. Comparatively few studies, however, have calculated credible EROEI values for cellulosic ethanol from wood.

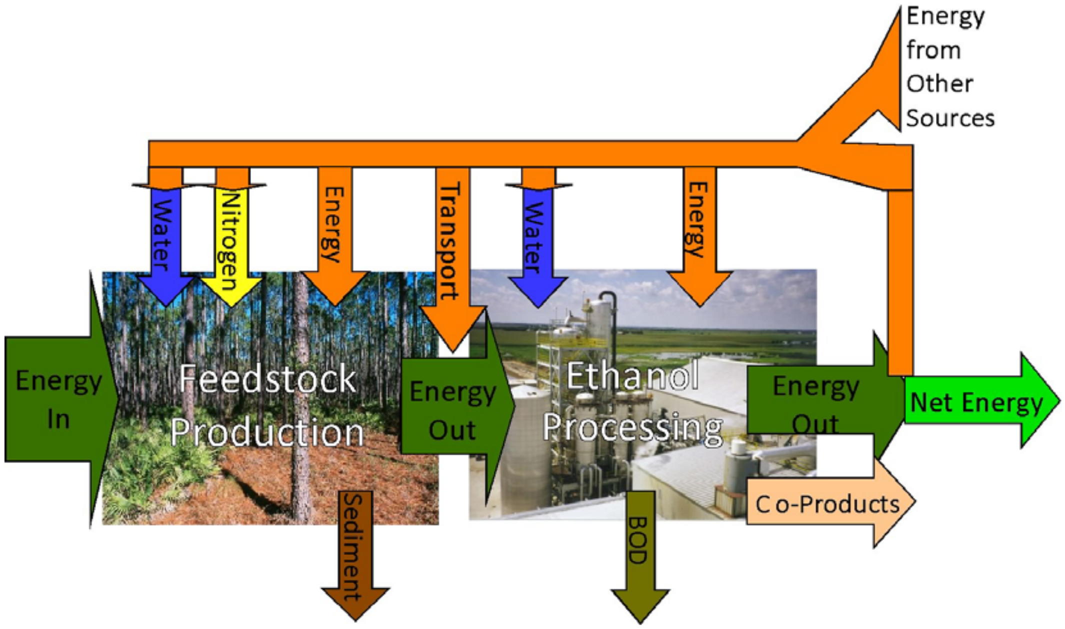

Fig. 1 – Net energy of ethanol production; water, nitrogen and land area requirements per net energy production are one proposed means of evaluating environmental consequences of large scale production. Sediment production (erosion) and BOD load are others, not considered here.

Net energy is fundamental to predicting water resource impacts because low EROEI values indicate that much of the energy produced must be appropriated to maintain the process (orange arrows in Figure 1), thus amplifying water, nitrogen and land requirements to meet actual societal demand. For example, if the EROEI is 2.0 (that is, energy yield is twice energy invested), water, land or nitrogen use per liter of gross production will be only half of what's actually required to yield that energy in a life-cycle setting. Similarly, an EROEI value of 1.25 will underestimate by a factor of 5 the environmental resources required.

Our analysis of four feedstocks suggests stark and important differences in net energy. Corn ethanol production in Florida would, under optimal conditions, have an EROEI of 1.26:1, even after accounting for co-product (dry distiller grains, an animal feed) output (EROEI is 1.05:1 without co-product credits). This is consistent with numerous studies suggesting positive but small net energy for corn ethanol processes. By contrast, EROEI for ethanol based on sugarcane grown in the muck soils of the Everglades Agricultural Area (EAA) is 2.51:1. Although this EROEI might appear to make Florida's sugarcane an attractive feedstock, high profit margins for table sugar will likely preclude use of the existing crop as a dedicated feedstock for the foreseeable future. Moreover, this supply is fundamentally geographically constrained – similar EROEO cannot be expected for production on non-muck soils. Sweet sorghum – a crop grown in similar climatic and soil conditions to corn, but converted into ethanol using a less intensive process – yields an EROEI of 1.94:1 after co-product credit for residual biomass combustion in a power plant, but only 1.28:1 without that credit. Finally, pine to ethanol has an EROEI of 2.97:1 when electricity from burning waste lignin is considered, and 2.49:1 without this co-product credit.

In short, all feedstocks we considered yield net energy, a non-trivial observation given recent literature. Moreover, there appear to be energetic reasons to select wood and sugarcane over corn; sweet sorghum, for reasons related to water and N use to be elaborated on below, may still be a desirable alternative. Recall, however, that sugarcane is confounded by the geographic scope of current production, and the unknown changes in inputs that would be required to achieve similar yields at other less favorable sites.

Discussion about energy production from biological feedstocks has not, as we do here, focused exclusively on dedicated energy crops. The magnitude of organic wastes generated from harvest operations and agricultural processing is enormous, and, with respect to life cycle energy and environmental costs, free. While it is somewhat misleading to treat harvest residuals strictly as waste, given their role in nutrient cycling and organic matter maintenance, it is reasonable to consider waste biomass resources for potential fuel production. The National Renewable Energy Laboratory maintains a county-by-county database of waste biomass by source. For Florida, total waste biomass is 9.6 million tons (40% from forest and mill operations, 34% from crop wastes). Assuming no additional energetic costs to collect and process this mass, and a generous 400 liters of ethanol yield per ton, waste could supplant less than 8% of current statewide fuel use, and less than 1/3 of the State's proportional EISA 2022 production mandates. This quantity, though modest compared to expectations, is significant and worthy of investment. However, it makes clear that emphasis on dedicated energy crops is essential.

It Takes Water…to Get Energy

Humans appropriate a significant and growing fraction of global primary production (estimates as high as 55% – Rojstaczer et al. 2001), and by extension, directly and indirectly appropriate the planet's available water to service human enterprise. Direct water use (i.e., municipal, industrial and irrigation supply) is estimated to be 4,400 km^3 globally, or approximately 10% of total riverine flux (Postel et al. 1996). While withdrawals associated with direct use clearly have significant hydrologic implications, indirect water use, which includes evapotranspiration by plants produced for people, is actually far higher (~18,000 km^3).

Water use to produce bioethanol occurs during both feedstock production and industrial processing. Water used during fermentation and distillation ultimately amounts to a relatively small amount. Most modern distilleries use between 5 and 10 liters of water per liter of ethanol, a number that has declined with efficiency improvements. Therefore, on a gross energy basis, meeting 2022 ethanol production goals would require 1.4 trillion liters of water annually, or roughly 0.25% of current US water use (566 trillion liters/year). While distillery water use on a net energy basis depends strongly on the feedstock, a net energy benefit of 2.5:1 would increase that number to only 2.3 trillion liters/yr.

Water use during feedstock production is more significant. While substantial variability in water use efficiency exists among feedstocks, increased productivity generally means greater water resource use. Crop productivity in many areas is highly dependent on irrigation, and withdrawals for irrigation (referred to as "blue water", Fig. 2) represent an unambiguous use of water. A somewhat less obvious, but potentially much more significant, water use during feedstock production is by increasing evapotranspiration rates across the landscape (referred to as "green water" use); this quantity is critical for a life cycle accounting of water use. Powell et al. (2005), for example, estimate differences in transpiration of 250 mm/yr between high density production forests and lower density conserved forests. Jackson et al. (2005) also report on the hydrologic effects of increased primary productivity at the watershed scale. Our estimates of water use for gross and net ethanol production consider total water use as the sum of green water (ET_{crop} vs. ET_{ref}), blue water, and the small amount of water necessary at the distillery.

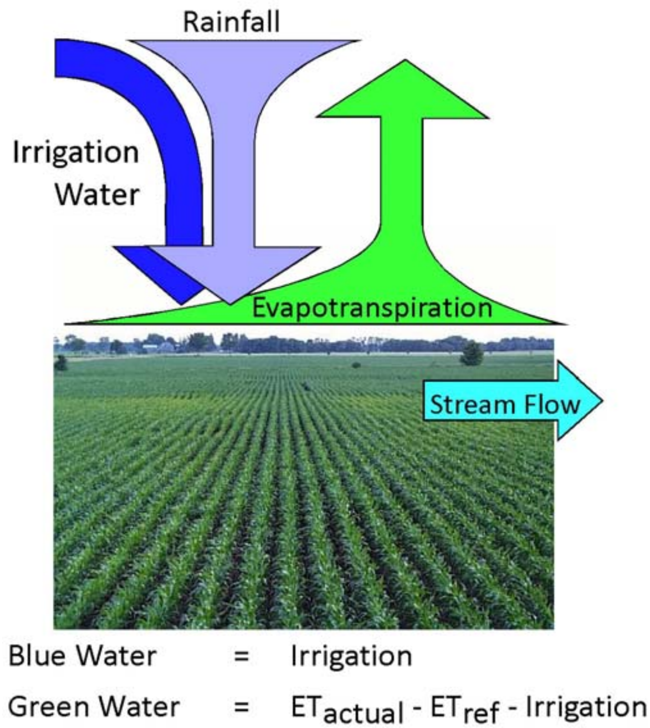

Fig. 2 – Distinction in water use between blue water (irrigation water appropriated from outside the system) and green water (excess ET above a reference value). The latter is an important means of evaluation for systems that are not irrigated, but exhibit high ET (e.g., southern pine plantations).

The most water use efficient feedstock on a net energy basis is sugarcane, which requires 10.1 m^3/GJ_{net}; while sugarcane is widely regarded as water intensive, the reference ET for marsh ecosystems in South Florida against which sugarcane transpiration is compared suggests that additional ET necessary for production is small. Were the analysis to extend beyond the EAA, much larger water use would likely be observed. Sweet sorghum (30.6 m^3/GJ) and wood (51.6 m^3/GJ) are next, while corn is most water intensive (188 m^3/GJ). Up-scaling these values makes the implications of this water use clear. Florida currently uses 114 billion m^3/yr (8.2 billion gallons per day). As such, offsetting 20% of current gasoline use, approximately the magnitude mandated by EISA, would increase total water use by 100% with wood, 60% with sorghum and 360% with corn. Impacts of this additional direct and indirect appropriation would likely be significant for flows and levels in Florida's lakes, aquifers and rivers. Notably, State law mandates setting of Minimum Flows and Levels, so regulatory protection exists that is likely to make meeting even these modest offsets problematic. In short, increasing reliance on appropriation of primary production for fuel production is highly likely to exacerbate old and engender new water resource challenges.

It Takes Nitrogen…to Get Energy

Anthropogenic control on global N cycling is clear and growing, presenting enormous challenges to maintenance of aquatic ecosystem integrity and productivity. Florida currently uses 275,000 tons of nitrogen fertilizer (as N) annually for food and fiber production, and landscaping. By comparison, rainfall wet deposition across the State is roughly 4 kg N/ha/yr, which translates into 69,000 tons of N. This human-induced increase has familiar consequences; estuaries and rivers are increasingly eutrophic, and the Floridan Aquifer, the State's principal water supply, has nitrate concentrations 1000% higher than pre-development in some areas.

The principal source of anthropogenic N loading is mineral fertilizer. While wastewater disposal is important, and animal operations can be locally significant, at the regional scale strong isotopic evidence supports the dominant role of fertilizers. Increasing agricultural productivity to meet biofuel production demand will likely intensify (resulting in greater N application rates to increase yields) and extensify (developing production systems on new, potentially marginal, lands) agriculture. Both would exacerbate N loading. The question is how much?

Before examining N loading associated with feedstock production, it's worth pointing out that a significant cost of using N fertilizer is energy required to produce it. Each kg of N fertilizer, fixed from the atmosphere using the Haber process, consumes 51.5 MJ of energy, currently supplied by natural gas. The 100 million tons of N production annually accounts for 4% of natural gas used globally. As such, increases in N use have consequences both on environmental systems and on life-cycle energy costs.

N requirements between feedstocks vary dramatically. Annual N use per hectare is 300, 40, 160 and 22.5 kg for corn, sugarcane, sweet sorghum and pine, respectively. When evaluated on a net energy basis, each GJ_{net} output requires 11.2, 0.4, 1.4 and 0.4 kg, respectively. Given Florida's gasoline demand (1.1 billion GJ), the implications of fuel replacement on N are large. On a gross basis (that is, ignoring energy required for production), N use per 1000 liters is between 6 (wood and sugarcane) and 59 (corn) kg N. At that rate, Florida's proportional EISA ethanol mandate for 2022 (~ 8.2 billion liters, ca. 20% of total demand) would require N inputs between 52,000 (southern pine) and 486,000 tons (corn).

On a net energy basis N requirements to offset just 10% of Florida's liquid fuel use would be 102,000 tons of N with southern pine, the most N efficient feedstock. In other words, 25% gasoline offset would double current N use. With corn, N requirements for 10% offset (1.9 million tons) are an order of magnitude higher than current use. Sweet sorghum, widely viewed as a desirable feedstock because of low N demand, would still require doubling N loading statewide to meet 25% of current fuel demand.

It Takes Land to…Get Energy

Land allocation is likely to be impacted by aggressive ethanol policies. Current trends in forest cover are starkly downwards with countervailing upwards trends in urban lands. Aggressive land acquisition by State and local agencies over the last decade to protect large, ecologically sensitive and/or corridor parcels for maintenance of wildlife populations and environmental services has been politically popular. This priority is likely to conflict with meeting even modest EISA biofuel production goals that may require major extensification of feedstock production. Land required for feedstock production, and resulting trade-offs that will ensue between competing priorities, have been insufficiently discussed.

Before considering land requirements for bioethanol production, note that feedstocks vary considerably in their ability to provide other ecosystem services. For example, our comparison among feedstocks does not consider stark differences in habitat value between corn or sweet sorghum fields (low) and production pine forests (high). These differences are hard to quantify in a life-cycle context, but should be prominent in discussions of bioethanol costs and benefits.

The land area necessary to produce ethanol is dependent on yields; sugarcane and sweet sorghum, where nearly all biomass is used to produce ethanol, have extraordinary yields in Florida (95,000 and 109,000 kg wet weight/hectare/year, respectively). On a gross basis, these two crops both require approximately 1,300 m^2 to produce 1000 liters of ethanol. Corn, where only grain yield is used for ethanol production, yields are lower (~12,500 kg/ha/yr) and more area is needed (~ 2,000 m^2 for 1000 liters). In contrast, pine plantation yields on an annual basis are low and lignin-rish (380,000 kg wet weight per 25 year rotation, or 15,200 kg/ha/yr) so to produce 1,000 liters of ethanol requires ~3,500 m^2. Up-scaling these gross values, which makes important and generous assumptions about the generality of reported yields, indicates that land area is not likely to be severely constraining. Meeting Florida's proportional EISA mandate (ca. 20% of current use) using the most land intensive feedstock (pine) would use only 20% of the total land area; sweet sorghum would require only 7% of the area.

However, as with water and N, a more appropriate and realistic focus is on area requirements to produce <u>net energy</u>. When life-cycle energy costs of ethanol production are considered, larger footprints to meet the same fuel mandates are required. Specifically, production from sorghum or sugarcane would require 16 and 14% of the total land, respectively; by way of comparison, this area is roughly double current crop land in the state. For corn, meeting that mandate (~20% of current demand) would require nearly 60% of the State be dedicated to production, which is clearly untenable. Finally, production from pine would require 33% of the State, approximately equal to the land currently occupied by both production and conserved forests (37%) suggesting that even modest offsets in liquid fuels will require land use transition (i.e., converting conserved forests to production), and massive market disruption in existing wood products industries.

Conclusions

Energy independence is clearly among the key 21st century challenges, underscored by recent escalating gasoline prices and observable effects of global climate change. Ethanol is widely viewed as a viable alternative: it locates energy production regionally, catalyzes national farm production, minimizes costs and logistics of infrastructural changes, and possibly limits CO_2 emissions. However, drawbacks of ethanol production with regard to environmental and social costs inextricably link consideration of energy alternatives to some of our other challenges. Among them: how we allocate increasingly scarce water amongst a growing array of users? How do we reverse nitrogen pollution in our rivers and estuaries? How do we conserve undeveloped lands for future generations of humans and other species? These and other trade-offs are the crucible within which aggressive bioethanol policies need to evaluated.

Analysis of ethanol production in the southeastern US, the presumptive epicenter of biofuel production because of long growing seasons and abundant rainfall, support several important conclusions. First, all four feedstocks (corn, sugarcane, sweet sorghum and wood) yield net energy over their life cycle. Second, even modest offsets of Florida's current liquid fuel consumption (e.g., EISA mandates of ~8.2 billion liters of ethanol annually, roughly 20% of current liquid fuel energy demand) would require irrigation volumes 5 times current water use (for corn) or 50% of current water use (for sorghum). While pine plantations in Florida aren't ordinarily irrigated, increased ET would be larger than total current water use to meet 20% of liquid fuel demand, with consequences for riverine base flows and regional aquifer levels. Potential N use is equally problematic; total N use in Florida would double (to 550,000 kg) with ethanol replacing 60%, 37%, 18% and 2% of current fuel use given wood, sugarcane, sweet sorghum and corn, respectively as feedstocks. Implications for regional aquatic health are obvious. Finally, productive land in Florida is already highly allocated for production of commodities, habitat and water quality protection, and growing urban demand. Land requirements for a biological solution to fuel demand are tremendous; it takes 375 m^2 of corn to produce a net GJ of fuel energy, nearly 210 m^2 of pine plantation, and nearly 90 m^2 of intensive sweet sorghum. To replace 20% of Florida's fuel use with ethanol from wood would require an area equivalent to all current forest land (production and conservation forest); similar estimates for sorghum and corn are 18% and 74%, respectively. Even if the entire Everglades Agricultural Area (ca. 300,000 ha) were used to grow sugarcane for ethanol, this would supply less than 15% of even the modest EISA mandates assumed for Florida based on that state's proportional use of gasoline. It is worth noting that meeting EISA mandates nationally is likely to require disproportionate contributions from southern states where annual primary productivity is high.

The policy implications are sobering. While it is clear that fuel alternatives are needed most urgently for the transportation sector, it is likely that bioethanol production at a scale that can meaningfully offset current liquid fuel demand would engender environmental costs that are likely to be considered unacceptable. As such, we contend that any serious discussion of policies to incentivize ethanol production be coincident with equally aggressive measures to enhance efficiency and, in the long term, dramatically reduce demand.

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