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The water footprint of biofuel production in the USA

> “…energy and water interdependence will play a key role in the ability to grow the crops needed for biofuel production without causing significant damage to the economy and the environment.”

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The US mandates for increased use of domestically produced biofuels will help to reduce the dependence on imported oil, yet it will necessitate the increased use of our earth and ecosystem services, our ‘natural capital’. Biofuels can be sustainably produced if we recognize the limits of our soil, water and air resources to provide these services. Many of the dedicated crops used for biofuels have a significant water footprint. That is, they consume water for growth and evapotranspiration, and a fraction of the agrochemicals used to obtain higher yields are leached into surface water bodies. This opinion summarizes the extent of this water footprint and explores mechanisms for reducing the resulting impacts.

The US Energy Independence and Security Act (EISA) of 2007 mandates an increase from the approximately 8.5 billion gallons a year (BGY) of biofuels produced in the USA in 2008 to 36 BGY by 2022, including 15 BGY of corn-based fuel ethanol by 2015. The drivers behind this policy include energy security and independence, increased markets for US-grown corn and the value of biofuel versus fossil fuel combustion in terms of reduced net increases in atmospheric carbon dioxide and other air pollutants.

Biomass resources should be used in recognition of these valuable attributes. However, we must also recognize that increasing the rate of biofuel consumption will necessitate the increased use of our earth and ecosystem services, our ‘natural capital’. There is a limit to the capacity of our air, water and soil ecosystem services to provide biomass for fuel at a sustainable rate. Unless substantial improvements in corn and ethanol yields are realized, the increase in biofuels production will result in greater areas of land used for dedicated feedstock production. Based on the modeling efforts of a US interagency biomass task force [101], it is estimated that 3.7 million additional acres will be required to produce 15 BGY of corn ethanol in the USA (estimated with regional environmental and agricultural programming [REAP] model) in comparison with their baseline estimate of 12 BGY ethanol from corn in 2016 [101]. This includes over 1 million acres that are currently in the conservation reserve program (CRP). This increase in land use, especially the increase in the use of marginally productive lands, is likely to also result in increased water, fertilizer and pesticide use, and soil lost to erosion.

The impacts of increased biofuels production on water quality and quantity have recently been added to the overall biofuels debate as important environmental issues [1–3]. Significant quantities of water are used as an input to the overall ethanol production process, especially for growing row crops that are increasingly used as bioenergy feedstocks. A substantial increase in water pollution by fertilizers and pesticides is also likely, with the potential to exacerbate eutrophication

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and hypoxia in areas including Chesapeake Bay and the Gulf of Mexico [4,102]. This in turn would cause undue financial hardship on the fishing industry, as well as negative impacts to these vital, biodiversity-rich ecosystems. Such threats to water availability and quality on local to national scales represent a major obstacle to sustainable biofuel production and require careful assessment of crop selection and management options.

This opinion summarizes the results of our research on the 'water footprint' of biofuels, which integrates water quantity and water quality issues [2]. We aim to increase the audience's awareness of these issues and to recommend changes in the industry that are necessary for biofuels to have a sustained and sustainable role in our energy future.

The water footprint of biofuels

Water quantity issues

When considering the overall lifecycle of biofuel production, almost all of the water consumption occurs during agricultural activities necessary to produce feedstocks. Water requirements for feedstocks range from approximately 500 to 2000 liters of water per liter of ethanol produced (Table 1), to approximately 1000 to 4000 liters of water for soybeans per ethanol-equivalent liter of biodiesel produced [2]. By contrast, ethanol refining facilities consume approximately 2–10 liters of water per liter of ethanol produced [1].

The wide range of water requirements for biofuels depends on how the water demand is defined, the type of feedstock used and soil and climatic variables. It is important to differentiate between agricultural water withdrawals and agricultural water consumption [1].

Table 1. Water use for selected US biofuel crops (liters water per liter ethanol).

	Evapotranspiration[‡]	Irrigation[§]
Sugar beet	812	1080 ± 590
Corn grain	1260	566 ± 340
Sugar cane	1270	1680 ± N/A
Switchgrass[¶]	1400	N/A ± N/A
Sorghum	2020	1520 ± 422
Soybean[#]	4190	1260 ± 401

[‡] Based on UNESCO report 'The water footprint of nations' except for switchgrass.

[§] Irrigation estimates represent the average only of that fraction of the crops that are irrigated based on 2003 NASS statistics.

[¶] Data for switchgrass from a variety of literature sources.

[#] Soybeans for biodiesel: denominator in terms of energy equivalent volume of ethanol (0.64 J ethanol/J BD).

Data from [2].

Water withdrawals for irrigation are more easily measured, but they do not necessarily correspond with the actual consumption of water by plants for growth and evapotranspiration. In many cases, much of the water consumption may come directly from rain. However, any incremental increase in the redirection of rainwater through the biofuel crop system (i.e., relative to pre-existing land cover) makes it no longer available to replenish surface or groundwater water supplies. In the USA, agriculture accounts for 40% of total water withdrawals and for 80% of total water consumption. Therefore, any agriculture-intensifying policy needs to be carefully assessed in order to avoid water problems.

Both corn grain and switchgrass currently compare favorably to other fuel crops regarding irrigation requirements (withdrawals) (Table 1). Irrigation rates for corn are lower compared with other crops, because corn is grown primarily in regions with adequate rainfall. Indeed, very few acres are irrigated in the humid areas of Ohio and Illinois, but almost all corn is irrigated in the drier climates of Nebraska and eastern Colorado. A study by Chiu *et al.* illustrates that corn production for ethanol is increasingly taking place within areas requiring irrigation [4]. The study reports that consumptive water appropriation by corn ethanol in the USA increased 246% between 2005 and 2008 (from 1.9 to 6.1 trillion liters of water), whereas corn ethanol production increased only 133% (from 15 to 34 billion liters). Similarly, although the theoretical irrigation water requirement for prairie-grown switchgrass is zero, biomass yields can vary substantially with precipitation [5], with as much as a fivefold increase in regions with high precipitation [6]. Thus, it is expected that irrigation in drier regions will be utilized as farmers strive to maximize the yield of a switchgrass crop.

A simple comparison can provide some perspective on how much water is consumed by irrigated biofuels. A car could consume 50–100 gallons of water for each mile driven on ethanol. Assuming a conservative volumetric water to ethanol ratio of 800 (e.g., for irrigated corn ethanol from Nebraska), and that a car can drive 16 miles on one gallon of ethanol (or two-thirds of the mileage from gasoline), this represents approximately 50 gallons of water per mile driven (gwpm). This could increase to 90 gwpm if sorghum ethanol from Nebraska is used, or 115 gwpm if the sorghum is grown in Texas. By contrast, considering water consumed during petroleum extraction and refining into gasoline [7], an average US car essentially consumes 0.2–0.5 gwpm.

Water quality issues

Meeting the near-term mandated increased production of corn ethanol in the USA is expected to increase agrichemical use, leading to adverse water quality impacts that range from local groundwater degradation to eutrophication of distant coastal waters.

Pesticides, including atrazine, alachlor, glyphosphate and 2,4-D, are commonly used for dedicated crops used for biofuels [103]. The use of glyphosphate on corn is growing rapidly owing to the switch to over 50% of corn acreage being planted with 'round-up-ready' corn (glyphosphate is the active ingredient in this commercial herbicide) [104]. Herbicides are also used for switchgrass, especially in the first couple of years of the perennial cycle to kill broad leaf weeds as the grass plants are established [5]. The impact of these agricultural pesticides on water quality continues to be studied, although there are limited data to estimate leaching rates and the resulting impacts are often hotly debated. For example, in a study in 2003, atrazine was implicated as an endocrine disruptor contributing to mutations in frogs even at very low concentrations [8]. More recent studies, however, have shown this to not be the case [9].

Nitrogen and phosphorous fertilizers are the primary contributors to hypoxic zones worldwide (hypoxia is a state of very low oxygen levels, <2–3 mg/l oxygen, that cannot sustain marine life. In simple terms, it results from the additions of nutrients to the water body, which causes significant algal growth and then the consumption of available oxygen to degrade the algae as it dies) [10]. The shallow coastal hypoxic zone of the Gulf of Mexico covered over 20,000 km^2 in the summer of 2008 [105]. The size of this zone, which varies with the seasons, the total discharge of nutrients from the Mississippi–Atchafalaya River Basin (MARB) and weather patterns, has generally increased since the 1950s. This is directly, although not solely, attributable to the increased fertilization rates and row crop acreage in the Mississippi River basin [11] and the resulting nonpoint source discharge of the fertilizer to surface water bodies throughout the basin. This hypoxic zone is of particular concern because it threatens Gulf fisheries that generate approximately US$2.8 billion annually [106].

Annual row crops, such as those currently used as biofuel feedstocks, are especially prone to nonpoint source pollution. Corn has one of the highest rates of nutrient application (38 ± 9 g N/l ethanol) [2] and nutrient discharge to surface waters. On a global basis, discharges of nitrogen to surface water bodies are equal to a quarter to a third of the combined fertilization

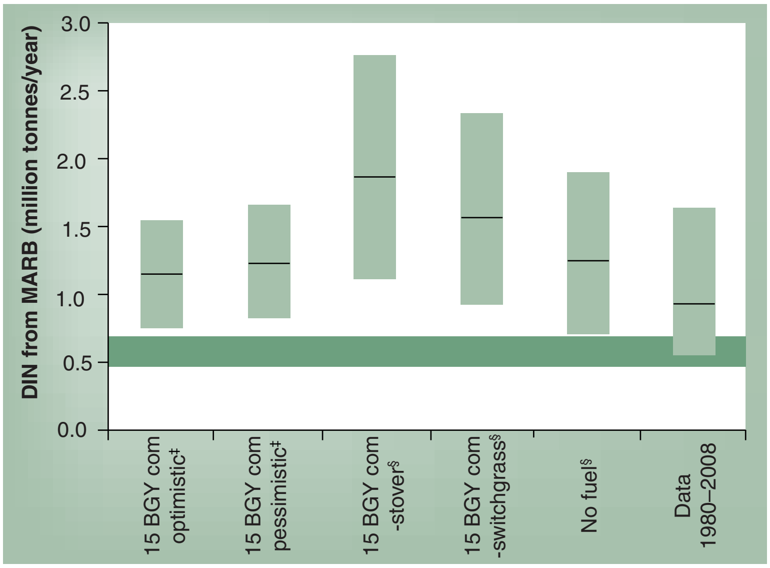

Figure 1. Actual [107] **and predicted** [3,19] **total dissolved inorganic nitrogen loads (mass/year) delivered from the Mississippi–Atchafalaya River Basin to the Gulf of Mexico.** The dark gray horizontal bar represents the range of loads required to meet the <5000 km^2 goal for the size of the hypoxic zone [3].

‡Data from Donner and Kucharik represent the range of DIN discharges in 2015 with optimistic and pessimistic corn and ethanol yields [3]. The bars include the mean value with 5–95% confidence intervals.

§Data from Costello *et al.* assume that the 15 BGY ethanol target in 2015 is achieved with both corn and corn stover feedstocks and the 2022 target of 35 BGY ethanol will be derived from switchgrass [19]. Costello *et al.* also modeled the 'no fuel' scenario with increased food, feed and fiber production expected by 2015, but with no dedicated crops used for fuel production. Data on actual DIN discharges from the MARB to the Gulf of Mexico are from the USGS [107]. The USGS and Costello *et al.* data include the mean value and 10–90%.

BGY: Billion gallons a year; DIN: Dissolved inorganic nitrogen; MARB: Mississippi–Atchafalaya River Basin; USGS: United States Geological Survey.

and biological nitrogen fixation inputs of nitrogen to agricultural systems [12]. In the US Corn Belt region, a compilation of measured values show that typically 15–36% of the nitrogen in fertilizer applied to corn acreage is leached from the fields to surface waters through runoff, sediment transport, tile drainage and subsurface flow [13]. This fraction can vary substantially, from 5 to 80% in extreme years of drought and flooding, respectively [14,15]. By contrast, the results of an agricultural modeling study predicted that the average loss of total nitrogen from switchgrass grown in Iowa to surface water would be only 4% of the nitrogen in applied fertilizer [16]. Especially in regions with tile drainage, growing perennial grass crops can reduce the nitrogen fertilizer losses substantially compared with traditional row crops [17].

The mass of nutrients discharged annually from the US Corn Belt to the Gulf of Mexico, which is defined here as the 'nutrient load,' depends on the annual regional rainfall, total nutrient application, land usage for crops and agricultural practices. Efforts to predict the size of the hypoxic zone [18] and extrapolate nutrient loads resulting from EISA have been attempted [3,19]. **Figure 1** illustrates the recent historical range of dissolved inorganic nitrogen (DIN) loads to the Gulf of Mexico ('data') and the loads predicted to reduce the size of this dead zone to the targeted 5000 km^2 (dark gray bar) [107]. Two separate research groups [3,19] predicted nitrogen loads that are substantially higher than the targeted levels if EISA biofuel mandates are met. Predicted loads from switchgrass as a feedstock are clearly less than corn, but still much higher than the target [19]. The two studies used different methodologies and data in their modeling efforts, resulting in different quantitative projections. Regardless of these differences, the final conclusion remains the same – it will be very difficult to meet both hypoxia reduction goals while increasing our domestic biofuels production, even with the transition to using perennial cellulosic feedstocks.

▪ Policy role in the smart growth of biofuels production & use

The overall water footprint associated with biofuels must recognize the impact of increased land use for fuel production on water quality and water consumption. These impacts are inherent in traditional agriculture practices, so any increase in the demand for these crops will exacerbate water-related impacts unless substantial changes in agricultural yields or practices are realized [101]. Furthermore, marginal lands recovered from the conservation reserve program, which require even higher fertilizer application and are more susceptible to erosion and runoff, are expected to be pressed into agricultural service [4,101] to take advantage of beneficial crop prices, thereby exacerbating impacts on water quality. Changes in current affairs can go a long way to help mitigate the problems.

The problems of nonpoint source nutrient pollution can be reduced [20]. A variety of agricultural practices would help, including contour farming, reduced nitrogen application, grassed waterways, restored wetlands and no-till or conservation tillage agriculture [21,22]. Secchi *et al.* [22] analyzed the costs of some of these methods for farms in Iowa and showed the cost–effectiveness of reducing nutrient losses, especially from tile-drained land [23]. Nitrogen losses would likely also be reduced with an increased price on nitrogen fertilizer or a system of nitrogen run-off trading between point and nonpoint sources [24].

The overconsumption of water for irrigation and degradation of water quality are environmental externalities, which are costs that are not borne by the feedstock or biofuel producer, nor the fuel consumer. Thus, federal and state policies are required to affect any changes to reduce the significant impact increased reliance on biofuels will have on water resources in the USA. Voluntary efforts, including implementation of best management practices (BMPs), can help [108], but stronger drivers for change – regulations, taxes, incentives – are often also required to shift the burden of external costs from society to the producer. The promotion of crop choices suitable for a given climate and the adoption of land-use practices that maximize biomass yields while efficiently utilizing nutrients and minimizing erosion are needed. Practices such as co-cropping winter grains and summer biomass crops, establishing riparian buffers and filter strips and no-till cultivation can help to reduce deleterious impacts of increased land use required for biofuel production. Similarly, rather than reducing the land allowed in the CRP, the program could be modified to promote dedicated cellulosic crops in former CRP lands. Encouraging this approach rather than reverting marginal lands to row crops for biofuel production could help to reduce erosion and runoff. CRP-like payments would then help to balance societal goals with ecological benefits and provide financial viability for the farmers making the land use choices. Policies and programs should be coordinated to avoid the current situation where some efforts (ethanol subsidies and mandates) bid against other programs

(CRP and hypoxic zone reduction), although all are funded by taxpayers with the intended common goal of environmental protection.

The biofuel and transportation industries must also recognize that major gains in efficiencies along the entire biofuel production and use lifecycle will directly increase the sustainability of the transportation sector. Thermochemical processes, for example, have the potential to provide higher biofuel yields per quantity of biomass than enzymatic processes [25] and thereby reduce acreage, water and agrichemical demands. As representatives of the biofuel industry and as consumers, we should also demand increased vehicle fuel economy standards so that sustainable biofuel production rates can indeed contribute in a substantial way to our liquid fuel needs. Without these increased efficiencies throughout the fuel lifecycle, the USA runs the risk of striving for biofuel production rates that are incompatible with the limits of the country's ecosystem services and the desire to displace imported fuels.

Overall, the USA cannot expect a major shift in their energy supply from oil fields to the farm fields to occur without some detrimental impacts. Evaluating the water footprint of this shift is critical to help policy makers implement a robust and environmentally sustainable national biofuels program. Clearly, the energy and water interdependence will play a key role in the ability to grow the crops needed for biofuel production without causing significant damage to the economy and the environment.

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