The Water Footprint of Biofuels: A Drink or Drive Issue?

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Brief: The implications of increased biofuel-driven agriculture on water resources availability and water quality degradation are addressed.

Introduction

Ensuring inexpensive and clean water is an overriding global challenge noted as one of the Millennium Development Goals of the United Nations. This challenge will likely be intensified by the increasing demand for biomass-derived fuels (i.e., biofuels) for transportation fuel needs, because (1) large quantities of water are needed to grow the fuel crops, and (2) water pollution is exacerbated by agricultural drainage containing fertilizers, pesticides and sediment. These potential drawbacks are balanced by biofuels’ significant potential to ease dependence on foreign oil and improve trade balance while mitigating air pollution and reducing fossil carbon emissions to the atmosphere. In the U.S., the Energy Independence and Security Act (EISA) of 2007 mandated the annual production of 56.8 billion liters of ethanol (15 billion gallons per year [BGY]) from corn by 2015 and an additional 60.6 billion liters (16 BGY) of biofuels from cellulosic crops by 2022 [1], a total that represents 15 % of the gasoline used in the U.S. in 2006 on an energy basis. The EISA requirements virtually guarantee a large increase in biofuel production. Furthermore, this mandated and subsidized change will occur largely free from the
market pressures and environmental constraints that would normally apply. The ongoing, rapid growth in biofuels production could have far-reaching environmental and economic repercussions, and it will likely highlight the interdependence and growing tension between energy and water security.

Developing a sustainable national biofuels program requires careful consideration of logistical concerns (e.g., suitable production and distribution infrastructure) and of unintended environmental impacts. Numerous recent studies have considered the latter, with a primary focus on air quality [2-4], land use [5-7], and net energy value [8-13]. These studies generally reflect beneficial environmental tradeoffs for biofuels compared to fossil fuels, with a few notable exceptions that recently considered greater CO₂ emissions associated with massive deforestation in tropical regions [6, 8, 14]. However, the effect of increased biofuels production on water security has not been subjected to the same scrutiny [15]. As biofuels production increases, a growing need exists to understand and mitigate potential impacts to water resources, primarily those associated with the agricultural stages of the biofuel life cycle (e.g., water shortages and water pollution) – herein referred to as the water footprint.

**Are we ready for 50 gallons of water per mile driven?**

The water requirements of biofuel production depend on the type of feedstock used and on geographic and climatic variables. Such factors must be considered to determine water requirements and identify critical scenarios and mitigation strategies. Feedstock cultivation, usually row-crop agriculture, is the most water-intensive of biofuel production stages. For example, evapotranspiration water requirements to produce enough feedstock to make one liter of ethanol in the U.S. range from 500 to 5,000 liters (Figure 1) while processing water requirements for a typical sugar cane or corn ethanol refinery are only 2 to 10 liters of water per
liter of ethanol produced \[15\]. Nevertheless, the water used in biofuel processing and other stages in biofuel production is often withdrawn from local point sources and can have localized impacts on water quality and quantity.

The water requirements associated with driving on biofuels can be significant \[16\]. Assuming conservatively a volumetric water to ethanol ratio of 800 (e.g., for irrigated corn ethanol from Nebraska, which excludes processing water requirements), and that a car can drive 16 miles on one gallon of ethanol (or 2/3 of the mileage from gasoline), this represents about 50 gallons of water per mile driven (gwpm). To illustrate the variability of the water requirement as a function of the crop used and where it is grown, this value could decrease to 23 gwpm for corn grown in Iowa, or increase to 90 gwpm if sorghum ethanol from Nebraska is used, or to 115 gwpm if the sorghum is grown in Texas.

![Figure 1. Evapotranspiration, irrigation and land requirements to produce one liter of ethanol (Le) in the U.S. from different crops.](image)

To minimize the water footprint of biofuels, it is important to recognize that some crops yield more biofuel energy with lower requirements for agricultural land, fertilizer and water, and
that consumptive water (evapotranspiration) requirements tend to increase with land requirement (Figure 1). Thus, from a water supply perspective, the ideal fuel crops would be drought-tolerant, high yield plants grown on little irrigation water. Currently, evapotranspiration requirements for fuel crops range in the U.S. from about 800 L of water per L ethanol produced (Lw/Le) for potatoes to about 4,200 Lw/Le for soybean [17]. To put these numbers in perspective, large quantities of water are also needed to produce energy from traditional sources (e.g., to pump petroleum out of the ground, generate steam to turn turbines, or nuclear power plants cooling water). However, the water requirements to produce an equivalent amount of energy from biofuels are comparatively large (Table 1)

<table>
<thead>
<tr>
<th>Process</th>
<th>L/MWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Petroleum extraction</td>
<td>10-40</td>
</tr>
<tr>
<td>Oil refining</td>
<td>80-150</td>
</tr>
<tr>
<td>Oil shale surface retort</td>
<td>170-681</td>
</tr>
<tr>
<td>NGCC* power plant, closed loop cooling</td>
<td>230-30,300</td>
</tr>
<tr>
<td>Coal Integrated Gasification Combined-Cycle</td>
<td>~900</td>
</tr>
<tr>
<td>Nuclear power plant, closed loop cooling</td>
<td>~950</td>
</tr>
<tr>
<td>Geothermal power plant, closed loop tower</td>
<td>1,900-4,200</td>
</tr>
<tr>
<td>Enhanced Oil Recovery</td>
<td>~7,600</td>
</tr>
<tr>
<td>NGCC*, open loop cooling</td>
<td>28,400-75,700</td>
</tr>
<tr>
<td>Nuclear power plant, open loop cooling</td>
<td>94,600-227,100</td>
</tr>
<tr>
<td>Corn ethanol irrigation</td>
<td>2,270,000 - 8,670,000</td>
</tr>
<tr>
<td>Soybean biodiesel irrigation</td>
<td>13,900,000 - 27,900,000</td>
</tr>
</tbody>
</table>

* Natural gas combined cycle

Figure 1 shows that both corn grain, which is the most common fuel ethanol crop in the U.S., and switchgrass, which is a lignocellulosic crop, compare favorably to other fuel crops regarding water and land requirements. In fact, the theoretical irrigation water requirement for prairie-grown switchgrass is zero. Nevertheless, despite intensive research activity on plant
genomics and metabolic engineering to facilitate conversion of lignocellulosic feedstock into biofuels, current technology is not yet economically feasible to meet our large biofuel requirements from such feedstocks [19]. Consequently, an initial reliance on corn ethanol appears unavoidable to reach the current EISA mandate.

Will the biofuels mandate cause water shortages?

Expansion of corn acreage and associated irrigation requirements will have different consequences depending on where it occurs. Rainfall can satisfy most of the agricultural water requirements for biofuel production in some regions (e.g., Iowa, where only about 1% of the corn acreage is irrigated with less than 400 Lw/Le, or Ohio which also irrigates only about 1% of the corn but uses 1,400 Lw/Le (Table S6A, SI), while other regions rely primarily on irrigation (e.g., Nebraska where 61% of corn acreage is irrigated and uses about 800 Lw/Le, as detailed in SI). This spatial variability, as well as temporal variability in rainfall, makes it difficult to predict how increased irrigation requirements will exacerbate competition for water and create local water shortages. Nevertheless, some general inferences can be made at a national level.

The mandated annual production of 57 billion liters (15 BGY) of fuel ethanol from corn by 2015 represents a requirement of 44% of the 2007 U.S. corn production. To estimate the corresponding impact on irrigation requirements, we assumed that the percentage of the total corn acreage that would be irrigated remains at the 2002 level of 19% (Table S7 in SI), and that 566 liters of water are needed for irrigation per liter of ethanol (2003 weighted-average irrigation requirement, Figure1). Accordingly, the irrigation water demand attributable to the mandate is about 6 billion m$^3$ per year (Table S5A in SI), which represents about 3% of total irrigation water use in the US in 2000 and is higher than the total water withdrawals (all uses) for the state of Iowa [20]. This preliminary analysis does not consider changes in water requirements due to
potential displacement of crops of different water intensity, or how advances in biotechnology and improvements in harvest yields and conversion efficiencies might affect this demand. Note that about 5.5 BGY of corn ethanol are already being produced towards meeting the EISA mandate (Section D, SI); thus, the incremental demand for irrigation water is lower than the above estimate (Table S5B in SI). Nevertheless, regional impacts to water resources as a result of corn ethanol irrigation are already being experienced.

Most biofuel feedstock expansion is occurring in the Midwest [21]. In Nebraska, irrigated corn area surpassed all time highs in 2007 and 2008, with over 3.64 million ha planted. The area is also already in all time water deficits and legal actions have been taken by Kansas, based on allegations that Nebraska farmers used 98 billion liters more than their allotment of the Republican River in 2004 and 2005, as ruled by the Supreme Court in 2003. Meeting the Kansas demand would mean shutting off irrigation to an estimated 485,000 ha of Nebraska farmland [22]. The Ogallala Aquifer is also being drawn down at record rates, with an average draw down of 4 m across the 8-state region it underlies, and water levels have dropped by over 40 m in some areas [23]. These rates are expected to continue to increase to meet higher irrigation and ethanol process water needs.

But floods are common in the Midwest, so why is water availability a concern?

Extreme hydrologic events (droughts or floods) can impact feedstock production and availability. The 2008 floods and heavy rains in the Midwest washed away about 2% of the nation’s corn crop [21]. However, the nation-wide corn production from 32 million ha (79.3 million acres) is projected to be about 312 million tonnes (12.3 billion bushels), down 6 percent from the 2007 record, but up 17 percent from 2006 [24].
Extreme hydrological events are likely to persist according to the U.S. Climate Change Science Program [25], which infers that droughts will be more likely and severe in the Southwest, reducing regional water supply and increasing wildfire risks. Furthermore, cold season storms and floods will be more frequent in wet areas. On average, precipitation is likely to be less frequent but more intense, while heat waves are likely to increase and, consequently, more irrigation water would be necessary. Thus, in addition to geographical variability, temporal variability in water availability and in crop requirements confound our ability to determine the potential for biofuel irrigation to exacerbate competition for water resources and contribute to water shortages.

Energy and agriculture already rank as the top two sectors in U.S. water withdrawals, accounting respectively for 48% and 34% of the total [20]. Regardless of climate change, the competition for water between these two sectors will intensify in the near future. The Energy Information Administration’s (EIA) predicts that thermoelectric generation from coal, natural gas, nuclear and other fuels will increase by 22% between 2005 and 2030 [18], for example. Combined with a biofuel-induced increase in agricultural water use of 16.5% by 2015 (Table 2), the potential to create water shortages and conflicts cannot be dismissed.

**How will water quality be affected by the biofuel mandate?**

The overall water footprint associated with biofuels must recognize the impact of increased agricultural activity on water quality as well as water consumption. To meet the mandated increased production of biofuels, increased agricultural activity such as tilling more land and higher agrichemical application is inevitable, as are some adverse impacts that range from local groundwater degradation to eutrophication of distant coastal waters [26, 27]. Annual row crops such as those typically used as biofuel feedstocks are especially prone to cause soil
erosion and nutrient run off to surface water, with corn having the highest nutrient application rate and highest nutrient loading to surface waters on a per land area basis [28]. Furthermore, marginal lands that require even higher fertilizer application and are more susceptible to erosion and runoff may be pressed into agricultural service to take advantage of beneficial crop prices; which would increase impacts to water quality.

As shown above for water usage, agrichemical application rates vary widely among crops. Figure 2 presents the application rates for nitrogen fertilizer and pesticides available for bioenergy crops in a manner that normalizes the application rates to biofuel production potential. From the perspective of the total nutrient use, the nitrogen fertilizer demand attributable to the 15 BGY mandate is about 2.2 million tonnes/year (Table S5A, SI), which is about 16% of the value used annually for all crops in the U.S. [29].

Figure 2. Nitrogen and pesticide requirements for producing one liter of ethanol from different crops. Data are based on FRIS 2003 and NASS agricultural chemical usage datasets from the USDA. Data for pesticide application is not available for all crops.

*Soybean is used for biodiesel production; its requirements were estimated for an energy-equivalent volume of ethanol. This is a leguminous plant and only about 10% of the total soybean crop comes from N-fertilized fields. See additional details in the Supplemental Information, Table S6B.

The high fertilizer application rates, especially for row crops in the Midwestern U.S., provide the greatest fluxes of nitrogen and phosphorus to local waterways and the Mississippi River basin [30] and are considered one of the primary contributors to the growing hypoxic zone in the Gulf
of Mexico, which covered over 20,700 km$^2$ in 2008 [31]. The discharge of nutrients from the Mississippi River to the Gulf of Mexico has been measured by the USGS for decades (Figure 3) [32]. The total nitrogen (TN) load is comprised primarily of dissolved inorganic nitrogen (DIN), with organic and particulate nitrogen forms contributing 36% (±8% over 30-year history) of the TN load.

In 2001, the Mississippi River/Gulf of Mexico Watershed Nutrient Task Force completed an integrated assessment of the hypoxia problem, which led to a goal of reducing the size of the hypoxic zone to 5,000 km$^2$ by 2015 [33]. Recent estimates suggest that a 45% reduction in TN exports would be required to meet this goal [28] (solid black line in Figure 3). Donner and Kucharik employed a rigorous agricultural and process-based dynamic ecosystem model to predict the DIN load that will result from expanding production to meet the 15 BGY corn ethanol goals [34]. The symbols included in Figure 3 for the year 2015 are their predictions for the mean (± 95% confidence interval) DIN exports. The anticipated increase in corn cultivation would increase the annual average DIN load by 10–18%, which greatly exceeds the DIN export load targets. The role of phosphorous discharges in the formation of the hypoxic zone in the Gulf of Mexico has also been reassessed [35]; resulting in a new goal for a 45% reduction in TP exports (Figure 3).
Figure 3. Annual Nutrient loads from the Mississippi River at the St. Francis (USGS station number 07373420) and Atchafalaya River (07381495) sampling points [32]. The horizontal lines represent the goals for nutrient discharges defined to reduce the size of the hypoxic zone to 5,000 km$^2$ [28]. The 2015 symbols are projected DIN loads given increased biofuel crop production [34].

Nutrient loads to the Gulf of Mexico are highly dependent on the annual rainfall in the upstream Midwest each year [36], total nutrient application, and land usage for crops. For corn and soybean row crops, the average nitrogen discharged from the fields to surface waters through runoff, sediment transport, tile drainage and subsurface flow represents 24-36% of the nitrogen fertilizer applied, although this fraction can range from 5 to 80% in extreme years of drought (e.g., 1988, 2000, Figure 3) and flooding (1983, 1993) [30]. Land use and crop selection can greatly change the amount reaching surface waters. Nutrient discharges are greatest in the more humid corn and soybean regions across Illinois, Indiana, and Ohio [5, 34, 36, 37]. The presence of tile drainage in these areas of higher rainfall increases transport fluxes. In a modeling study comparing tile drained and non-drained soils in Iowa showed that the fraction of nitrogen fertilizer lost to surface waters ranged from an average of 8% in non-drained fields to 36% in tile drained fields [38]. The eastern regions of the Corn Belt contribute less to the water consumption aspect of the water footprint, but they contribute more to the water pollution component of the overall water footprint.

Less information is available regarding nutrient losses from other potential biofuel crops. The U.S. EPA Chesapeake Bay office [39] modeled the potential changes in nutrient loads resulting from increased biofuel production in the watershed, and projected a substantial reduction in nitrogen loads to the Chesapeake Bay if farmland is converted to switchgrass with no fertilizer (∼11,500 tonnes/y). In comparison, the Bay program partners are striving to reduce loads by 41 thousand tonnes from all sources. Thus, these changes will contribute substantially to that goal.
The assumption that no fertilizer would be used on the switchgrass fields in the Chesapeake Bay region is inconsistent with other reports that recommend between zero and several hundred kilograms of nitrogen fertilizer per hectare, with an average of 32 kg N/ha in available field trials (see SI). These discrepancies exist because of the lack of data associated with switchgrass cultivated as a cash crop, the uncertain relationship between fertilizer application and increased yields, and lack of field measurements quantifying the fate of the fertilizer in the soil, air and water after application. Switchgrass uses applied N efficiently [40], and appears able to obtain N from sources that other crops cannot tap. The long-term impacts on soil productivity are as yet unknown. In areas with sufficient rainfall, annual sustainable switchgrass yields of 15 tonnes/ha may be achievable by applying 50 kg N/ha [40]. The modeling study by Powers et al. assumed a much higher average fertilization rate for switchgrass grown in Iowa (0 kg/ha in year 1 to 260 kg/ha in years 6-8), and predicted that the average total nitrogen discharge to surface water would be 7.8 kg N/ha, representing 4.2% of the nitrogen fertilizer applied [38]. Although the fertilization rates were high in some years, a much lower fraction of fertilizer is lost to surface water with switchgrass than with corn.

**Land use changes that could impact water quality**

Prior to the current ethanol mandate and subsidies, fuel crops were generally grown where it was most economically and environmentally sound to do so. This was in part due to the conservation reserve program (CRP), which pays farmers not to utilize highly erodible and minimally productive lands. CRP contracts are ranked and selected based on the Environmental Benefits Index (EBI) to target retiring land from row crop production, which has the greatest detriment in terms of erosion, runoff, and leaching of nutrients. In 2007, over 14 million ha were enrolled in the CRP, producing notable reductions in pollutant loads to surface water, including
reductions of 187 million tonnes of sediment erosion, 218 thousand tonnes of nitrogen and 23 thousand tonnes of phosphorous [28]. The program was also reported to sequester an estimated 45 million tonnes of carbon per year [29]. Farmers are encouraged to plant CRP lands with native grasses or short rotation woody perennials including willow and poplar, which could also serve as biofuel crops. This selective planting clearly shows benefits of these crops on surface water quality, the overarching goal of the CRP.

Re-enrollment of lands in the CRP is dropping however, and participants are requesting early release from CRP contracts to take advantage rapidly rising biofuels crop prices, largely driven by EISA mandate and Federal subsidy in the form of the blender’s credit. In 2007, Secchi and Babcock estimated that over 526 thousand ha of Iowa farmland would likely be pulled from the CRP and put into a corn/soybeans rotation if corn prices hit $196 per tonne ($5 bushel) [7]. In June 2008, corn rose to nearly $314 per tonne ($8/bushel), well beyond the upper range modeled only one year earlier. Corn prices and futures have since stabilized between $157 - 196 per tonne ($4-5 per bushel), at the upper end of the 2007 estimates and well above the stable average or peaks of the previous two decades before the EISA mandate. Although CRP contracts are established on a 10 to 15 year basis, enrollment in the program is already decreasing. CRP enrollment dropped by more than 840 thousand ha in 2008. Due to the erodible and less-productive nature of most land enrolled in the CRP, removing land from the program for row crop production will likely lead to a non-linear increase in erosion and nutrient loading to surface waters. This trend is likely to continue as over 2.2 million ha are due to expire in the next three years, and the new farm bill also decreased the maximum area to be in the CRP by about 1.2 million ha. One proposal to avert removal of land from the CRP program is to increase CRP
payments, which totaled more than over $1.6 billion in 2007 [29]. However, some analysts suggest that even doubling the payments would not be sufficient to retain land in the CRP [7].

**Policy measures to mitigate the water footprint of biofuels**

The current and ongoing increase in biofuel production could result in a significant increase in demand for water to irrigate fuel crops, which could increase local and regional water shortages. A substantial increase in water pollution by fertilizers and pesticides is also likely, with the potential to exacerbate eutrophication and hypoxia issues in inland waters and coastal areas including Chesapeake Bay and the Gulf of Mexico. This, in turn, would cause undue financial hardship to fishermen as well as negative ecological impacts to these vital, biodiversity-rich ecosystems. Such threats to water availability and water quality at local to national scales represent a major obstacle for sustainable biofuel production and require careful assessment of crop selection and management options. It is important to recognize that certain crops such as switchgrass and other lignocellulosic options deliver more potential biofuel energy with lower requirements for agricultural land, agrichemicals and water. Biofuel crops should be selected to match climatic conditions and constraints, and regions where crops can grow on rainfall rather than on irrigation water should be favored.

Climatic factors such as frequency of droughts and floods are beyond human control, but as the wide range of estimated nutrients discharged to surface waters shows, clearly some important variables are within our control. These include crop selection, tillage decisions, and location. As more biofuel production is integrated into the agriculture sector it will be important to adopt land-use practices that efficiently utilize nutrients and minimize erosion, such as co-cropping winter grains and summer biomass crops. Similarly, a CRP-like program should consider promoting cellulosic biofuel crop planting in marginal lands as a way to prevent excess
erosion and runoff while still allowing producers to benefit from historically high commodity prices. CRP-like payments then would help balance societal goals ecological benefits and financial viability for the farmers making the land use choices. These land use choices should also focus on establishing riparian buffers and filter strips to serve a dual purpose in erosion control and biomass production. Finally, increasing charges for irrigation water for biofuels crops to market rates should be considered to promote fuel crop agriculture in areas where rainfall can supply the majority of the water requirements, and to reflect the true value of water resources in the price of biofuels. Policies and programs should be coordinated to avoid the current situation where some efforts (ethanol subsidies, mandates) work to bid against other programs (CRP), though both are funded by taxpayers with the common goal of environmental protection.

Overall, we can not expect a major shift in our energy supply from the oil fields of the Middle East to the farm fields of the Midwest to occur without some detrimental impacts. Evaluating the water footprint of this shift is a critical first step to provide input to policy makers to implement a robust and environmentally sustainable biofuels national program. Clearly, the interdependence between energy and water will play a key role in our ability to grow the crops needed for biofuel production without causing significant damage to the economy and the environment. However through energy conservation and careful planning that includes adoption of agricultural practices and crop choices that reduce water consumption and mitigate water pollution from agrichemicals, and identification of the local and regional water resources that will be needed to meet the biofuel mandate, we can have our drive and drink our water too. 

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Supporting Information available. Detailed descriptions of data sources and calculations for water, land, fertilizer and pesticide requirements are given in the Supporting Information section.

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