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Environ. Sci. Technol., 2009, 43 (9), 3005-3010 • DOI: 10.1021/es802162x • Publication Date (Web): 01 May 2009

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

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The water consumption and agrochemical use during biofuel production could adversely impact both availability and quality of a precious resource.

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 biofuel 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(s) while mitigating air pollution and reducing fossil carbon emissions to the atmosphere. In the United States, the Energy Independence and Security Act of 2007 (EISA) mandated the annual production of 56.8 billion L of ethanol (15 billion gal/yr [BGY]) from corn by 2015 and an additional 60.6 billion L (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. Although the growth rate of ethanol production in the current economic recession is uncertain, it vastly outpaced most U.S. industries in 2008, with record amounts of ethanol produced (>9 billion gallons) (2) and a corn harvest only slightly behind the 2007 record production (3). Continued growth 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 (4–6), land use (7–9), and net energy value (10–15). These studies generally reflect beneficial environmental trade-offs for biofuels compared to fossil fuels, with a few notable exceptions that recently considered greater CO₂ emissions associated with massive deforestation in tropical regions (8, 10, 16). However, the effect of increased biofuel production on water security has not been subjected to the same scrutiny (17). As biofuel 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 Fifty 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 in the U.S. necessitate 500–4000 L of water to grow enough feedstock to produce 1 L of ethanol (Lw/Le) (Figure 1); processing water requirements for a typical sugar cane or corn ethanol refinery are only 2–10 Lw/Le (17). 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 (18). 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 mi on 1 gal of ethanol (or 2/3 of the mileage from gasoline), this represents about 50 gal of water per mile driven (gwpm) (or 0.02 mi per gallon of ethanol driven). The gwpm increases according to the mix of water and ethanol in the fuel, with a maximum of 500 gallons per mile driven for pure ethanol, and a minimum of 80 gallons per mile driven for pure gasoline.

10.1021/es802162x © 2009 American Chemical Society
Published on Web 05/01/2009
regions rely primarily on irrigation (e.g., Nebraska where 61% of corn acreage is irrigated and uses about 800 Lw/Le, as detailed in the 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 L (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), and that 566 Lw/Le is needed for irrigation (2003 weighted-average irrigation requirement, Figure 1). Accordingly, the irrigation water demand attributable to the mandate is about 6 billion m³/yr (Table S5), which represents about 3% of total irrigation water use in the U.S. in 2000 and is higher than the total water withdrawals (all uses) for the state of Iowa (22). 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 is already being produced toward meeting the EISA mandate (Section D, SI); thus, the incremental demand for irrigation water is lower than the above estimate (Table S6). 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 (23). In Nebraska, irrigated corn area surpassed all time-highs in 2007 and 2008, with over 3.64 million ha planted. That area is also experiencing all-time water deficits and legal actions have been taken by Kansas, based on allegations that Nebraska farmers in 2004 and 2005 used 98 billion L more of the Republican River’s allotments permitted by the Supreme Court in 2003. Meeting the Kansas demand would mean shutting off irrigation to an estimated 485,000 ha of Nebraska farmland (24). The Ogallala Aquifer is also being drawn down at record rates, with an average drawdown of 4 m across the 8-state region it underlies, and water levels have dropped by over 40 m in some areas (25). These trends are expected to continue to increase as ethanol production increases.

**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.

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**Table 1. Water Requirements for Energy Production by Different Processes (20)**

<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>170–861</td>
</tr>
<tr>
<td>NGCCa power plant, closed loop cooling</td>
<td>230–30,300</td>
</tr>
<tr>
<td>coal IGCCb</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>1900–4200</td>
</tr>
<tr>
<td>EORb</td>
<td>~7600</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>

a Natural gas combined cycle. b Integrated gasification combined-cycle. c Enhanced oil recovery.
The 2008 floods and heavy rains in the Midwest washed away about 2% of the nation’s corn crop (23). However, the nationwide corn production from 32 million ha (79.3 million ac) is projected to be about 312 million t (12.3 billion bu), down 6% from the 2007 record, but up 17% from 2006 (26). Indeed, the most recent statistics show that field corn production in 2008 was down ~7% from 2007 and up ~15% from 2006 (3).

According to the U.S. Climate Change Science Program (27) extreme hydrologic events have become more frequent and intense in the past 50 years in the U.S., and this trend is likely to persist. Thus, in addition to the existing temporal and geographical distributions of water availability, the potential change in these distributions and its uncertain effects on crop yields and crop water demand confounds our ability to determine the implications of biofuel in future water supplies.

Regardless of climate change, the competition for water between sectors will intensify in the near future. Energy and agriculture already rank as the top two sectors in U.S. water withdrawals, accounting, respectively, for 48% and 34% of the total (22). The Energy Information Administration (EIA) predicts that thermoelectric generation from coal, natural gas, nuclear, and other fuels will increase by 22% between 2005 and 2030 (20). Combined with a biofuel-induced increase in agricultural water use of 6.2 x 10^12 L (6.2 billion m^3) by 2015 (Table S5), 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 (28, 29). Annual row crops such as those typically used as biofuel feedstocks are especially prone to cause soil erosion and nutrient runoff to surface water, with corn having the highest nutrient application rate and highest nutrient loading to surface waters on a per land area basis (30). 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: use of marginal lands would increase impacts on water quality.

Projecting Fertilizer Use on Current Lands. 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 (N) fertilizer demand attributable to the 15 BGY mandate is about 2.2 million t/yr (Table S5), which is about 16% of the value used annually for all crops in the U.S. (31).

The high fertilizer application rates, especially for row crops in the Midwestern U.S., provide the greatest fluxes of N and phosphorus (P) to local waterways and the Mississippi River basin (32) and are therefore considered one of the primary contributors to the growing hypoxic zone in the Gulf of Mexico (~20,700 km^2 in 2008) (33). The discharge of nutrients from the Mississippi River to the Gulf of Mexico has been measured by the U.S. Geological Survey (USGS) for decades (Figure 3) (34). The total nitrogen (TN) load is primarily dissolved inorganic nitrogen (DIN), with organic and particulate N 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 5000 km^2 by 2015 (35). Recent estimates suggest that a 45% reduction in TN exports would be required to meet this goal (36) (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 (36). 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 P discharges in the formation of the hypoxic zone in the Gulf of Mexico has also been reassessed (37); resulting in a new goal for a 45% reduction in total phosphorus (TP) exports (Figure 3).

Nutrient loads to the Gulf of Mexico are highly dependent on the annual rainfall in the upstream Midwest each year.
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 worsen 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 in inland waters and coastal areas including Chesapeake Bay and the Gulf of Mexico. 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 water quality on local and national scales represent a major obstacle to sustainable biofuel production and will 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.

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 methods, 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. 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. Similarly, a CRP-like program should be considered to promote cellulosic biofuel crop planting in marginal lands to prevent excess erosion and runoff while allowing producers to benefit from historically high commodity prices. 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. Finally, increasing charges for irrigation water for biofuel 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) bid against other programs (CRP) though both are funded by taxpayers with the common goal of environmental protection.

Overall, we cannot expect a major shift in our energy supply from the oil fields of the Middle East to the farmlands 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 national biofuels program. Clearly, the energy and water interdependence 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 agricultural methods and water usage planning, we can have our drive and drink our water too.

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Acknowledgments

R.D.-F. was financially supported by a fellowship from the Baker Institute Energy Forum, and by the Shell Center for Sustainability at Rice University. We thank Ada Y. Lee for her help in gathering input data, and Thomas Hayden for editorial advice.

Supporting Information Available

Detailed descriptions of data sources and calculations for water, land, fertilizer, and pesticide requirements. This information is available free of charge via the Internet at http://pubs.acs.org.

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