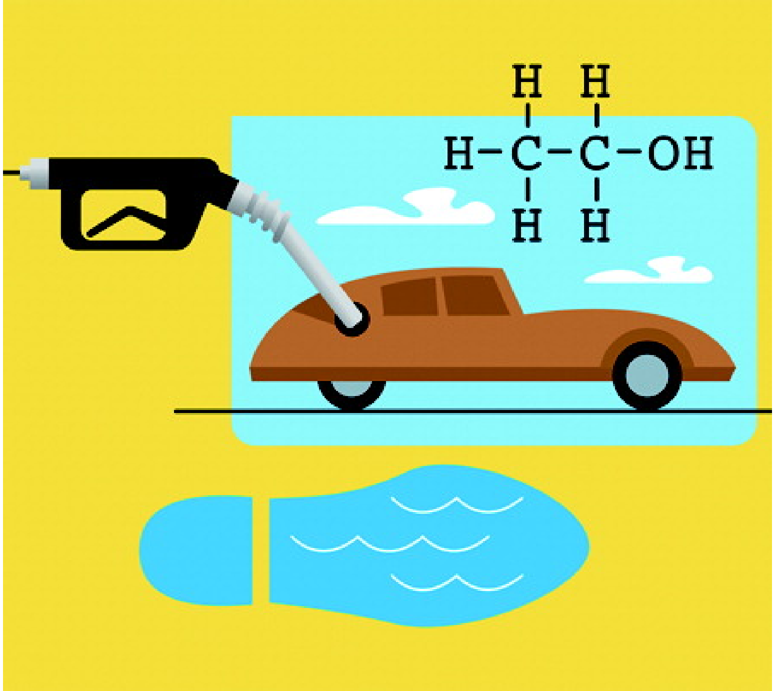
Environmental Science & Technology

Feature

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

R. Dominguez-Faus, Susan E. Powers, Joel G. Burken, and Pedro J. Alvarez

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



Environmental Science & Technology is published by the American Chemical Society. 1155 Sixteenth Street N.W., Washington, DC 20036

Environmental Science & Technology
Feature

Environ. Sci. Technol. **2009,** *43,* 3005–3010

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

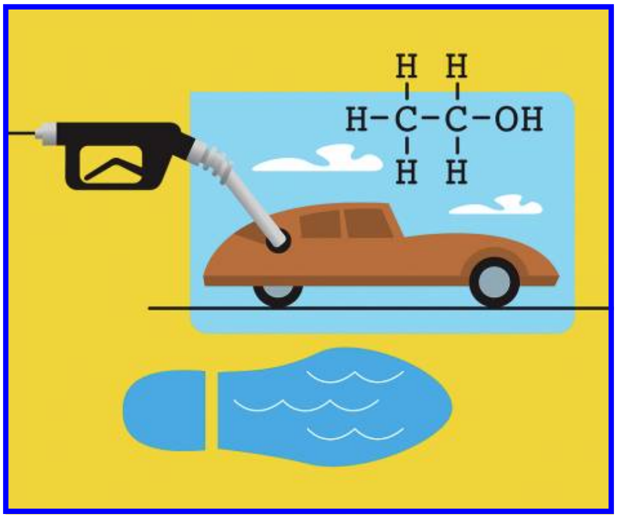
R. DOMINGUEZ-FAUS
Rice University

SUSAN E. POWERS
Clarkson University

JOEL G. BURKEN
Missouri University of Science and Technology

PEDRO J. ALVAREZ*
Rice University

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



SCOTT ROBERTS

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 CO_2 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

10.1021/es802162x

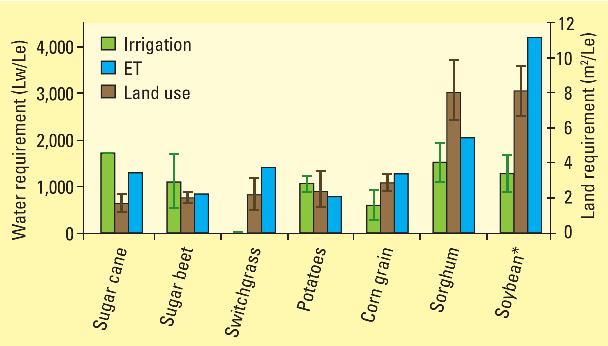


FIGURE 1. Evapotranspiration, irrigation, and land requirements to produce 1 L of ethanol (Le) in the U.S. from different crops. Weighted average ± 1 s.d. for top producing states, from U.S. Department of Agriculture (USDA) and other pertinent statistics as described in the Supporting Information (SI). Ethanol crops are not always irrigated (Table S9 in SI). Irrigation averages correspond to irrigated land only, while evapotranspiration and land averages correspond to total planted land. *Note that soybean is used for biodiesel production, and its water and land requirements were estimated for an energy-equivalent volume of ethanol.

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

Process	L/MWh
petroleum extraction	10–40
oil refining	80–150
oil shale surface retort	170–681
NGCC[a] power plant, closed loop cooling	230–30,300
coal IGCC[b]	~900
nuclear power plant, closed loop cooling	~950
geothermal power plant, closed loop tower	1900–4200
EOR[c]	~7600
NGCC, open loop cooling	28,400–75,700
nuclear power plant, open loop cooling	94,600–227,100
corn ethanol irrigation	2,270,000–8,670,000
soybean biodiesel irrigation	13,900,000–27,900,000

[a] Natural gas combined cycle. [b] Integrated gasification combined-cycle. [c] Enhanced oil recovery.

gal of water [mpgw]). To illustrate the variability of the irrigation water requirement as a function of the crop used and where it is grown, this value could decrease to 23 gwpm (~0.04 mpgw) for irrigated corn grown in Iowa, or increase to 90 gwpm (~0.01 mpgw) if irrigated sorghum ethanol from Nebraska is used, or to 115 gwpm (~0.009 mpgw) if the sorghum is irrigated in Texas.

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 Lw/Le for potatoes to about 4200 Lw/Le for soybeans (*19*). 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 and more consumptive (Table 1)

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 (*21*). 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 irrigates less than 1% of the corn but uses 1400 Lw/Le [Table S7]), 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 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 m^3/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.

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 6.2×10^{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.

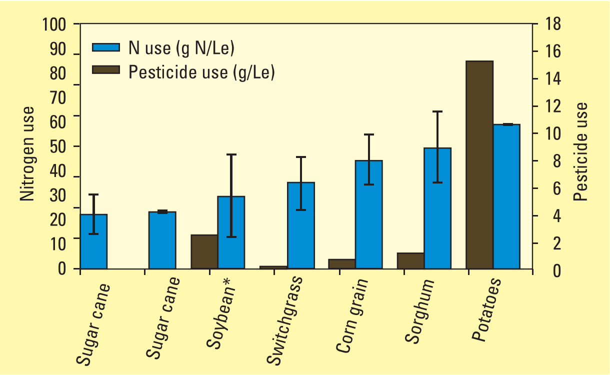


FIGURE 2. Nitrogen and pesticide requirements for producing 1 L of ethanol (if fertilized) from different crops. Data are based on FRIS 2003 and NASS agricultural chemical usage data sets from the USDA. Data for pesticide application are not available for all crops. *Soybean is used for biodiesel production; its requirements were estimated for an energy-equivalent volume of ethanol. In addition, soybean is a leguminous plant and only about 18% of the total soybean crop comes from N-fertilized fields. See additional details in Table S8.

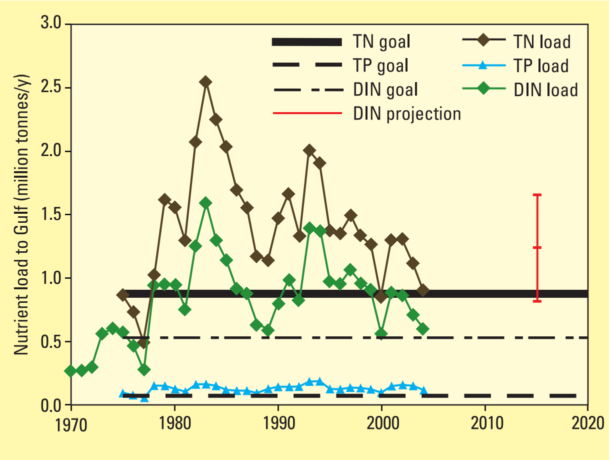


FIGURE 3. Annual nutrient loads from the Mississippi River at the St. Francis (USGS station 07373420) and Atchafalaya River (07381495) sampling points (*34*). The horizontal lines represent the goals for nutrient discharges defined to reduce the size of the hypoxic zone to 5000 km^2 (*30*). The 2015 symbols are projected DIN loads given increased biofuel crop production (*36*).

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 (*30*) (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

(*38*), total nutrient application, and land usage for crops. For corn and soybean row crops, the average N discharged from the fields to surface waters through runoff, sediment transport, tile drainage, and subsurface flow represents 24−36% of the N fertilizer applied, although this fraction can range from 5 to 80% in years of extreme drought (e.g., 1988, 2000, Figure 3) and flooding (1983, 1993) (*32*). 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 (*7, 36, 38, 39*). The presence of tile drainage in these areas of higher rainfall increases transport fluxes. In a modeling study comparing tile-drained and nondrained soils in Iowa showed that the fraction of N fertilizer lost to surface waters ranged from an average of 8% in nondrained fields to 36% in tile-drained fields (*40*). 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 (*41*) modeled the potential changes in nutrient loads resulting from increased biofuel production in the watershed, and projected a substantial reduction in N loads to the Chesapeake Bay if farmland were converted to switchgrass with no fertilizer (~11,500 t/yr). In comparison, the Bay program partners are striving to reduce loads by 41,000 t 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 kg of N 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 (*42*), 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 t/ha may be achievable by applying 50 kg N/ha (*42*). 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 N discharge to surface water would be 7.8 kg N/ha, representing 4.2% of the N fertilizer applied (*40*). 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 t of sediment erosion, 218,000 t of N, and 23,000 t of P (*30*). The program was also reported to sequester an estimated 45 million t of carbon (C)/yr (*31*). 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 requested early release from CRP contracts to take advantage of rapidly rising biofuel crop prices, largely driven by the EISA mandate and federal subsidy in the form of the blender's credit. In 2007, Secchi and Babcock estimated that over 526,000 ha of Iowa farmland would likely be pulled from the CRP and put into a corn/soybeans rotation if corn prices hit $196/t ($5/bu) (*9*). In June 2008, corn rose to nearly $314/t ($8/bu), well beyond the upper range modeled only one year earlier. Corn prices and futures stabilized through 2008 between $157−196/t ($4−5/bu) and overall 2008 averaged just over $160/t ($4/bu). This puts 2008 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 (e.g., the average price in 2005 was only $74/t ($1.9/bu) (*43*)). Although CRP contracts are established on a 10−15 yr basis, enrollment in the program is already decreasing. CRP enrollment dropped by more than 840,000 ha in 2008 and another 410,000 ha as of January 2009. 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 nonlinear 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 (*44*). One proposal to avert removal of land from the CRP program is to increase CRP payments, which totaled more than $1.6 billion 2007 (*31*). However, some analysts suggest that even doubling the payments would not be sufficient to retain land in the CRP (*9*).

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 lignocelluosic 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 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 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.

Rosa Dominguez-Faus is a Ph.D. candidate at the Civil and Environmental Engineering Department at Rice University, and a graduate fellow at the Energy Forum of the James A. Baker III Institute for Public Policy. She uses data mining, modeling, and environmental metrics calculations to enhance decision-making. Susan E. Powers is the Associate Dean of Engineering for Research and Graduate Studies and a Professor of Civil and Environmental Engineering at Clarkson University. Her work includes broad lifecycle research to provide environmental perspectives on fuels and energy systems. Joel G. Burken is a Professor of Civil and Environmental Engineering at The Missouri University of Science & Technology (formerly University of Missouri-Rolla). His research focuses on the phytoremediation of organic contaminants, plant sampling to delineate subsurface contaminants, and wetland treatment of metals from mining industries. Pedro J. Alvarez is the George R. Brown Professor and chair of the Department of Civil and Environmental Engineering at Rice University. Current research interests include environmental biotechnology and bioremediation, fate and transport of toxic chemicals; environmental implications of biofuels, and environmental nanotechnology. Please address correspondence regarding this article to alvarez@rice.edu.

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.

Literature Cited

(1) *Ethanol Myths and Facts; Department of Energy; Biomass Program*; U. S. Department of Energy: Washington, DC, 2008; p 3.
(2) Dinneen, R. *State of the Ethanol Industry Address*; 14th Annual National Ethanol Conference, San Antonio, TX, February 24, 2009; www.ethanolrfa.org/objects/documents//2009_state_of_the_industry.pdf.
(3) *Corn Grain Quick Stats*; National Agricultural Statistical Services, U.S. Department of Agriculture: Washington, DC; www.nass.usda.gov/Statistics_by_Subject/index.asp.
(4) Gaffney, J. S.; Marley, N. A. Alternative Fuels. In *The Urban Atmosphere and its Effects*; Brimblecombe, P., Maynard, R. L., Eds.; Imperial College Press: London, 2001; pp 195−246.
(5) Graham, L. A.; Belisle, S. L.; Baas, C. L. Emissions from light duty gasoline vehicles operating on low blend ethanol gasoline and E85. *Atmos. Environ.* **2008**, *42* (19), 4498–4516.
(6) Poulopoulos, S. G.; Grigoropoulou, H. P.; Philippopoulos, C. J. Acetaldehyde yield and reaction products in the catalytic destruction of gaseous ethanol. *Catal. Lett.* **2002**, *78* (1−4), 291–296.
(7) Donner, S. D.; Kucharik, C. J.; Foley, J. A. Impact of changing land use practices on nitrate export by the Mississippi River. *Global Biogeochem. Cycles* **2004**, *18* (1), article number GB1028.
(8) Searchinger, T.; Heimlich, R.; Houghton, R. A.; Dong, F.; Elobeid, A.; Fabiosa, J.; Tokgoz, S.; Hayes, D.; Yu, T. H. Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science* **2008**, *319* (5867), 1238–1240.
(9) Secchi, S.; Babcock, B. *Impact of High Crop Prices on Environmental Quality: A Case of Iowa and the Conservation Reserve Program*; Center for Agricultural and Rural Development, Iowa State University: Ames, IA, 2007.
(10) Dias De Oliveira, M. E.; Vaughan, B. E.; Rykiel, E. J., Jr. Ethanol as fuel: Energy, carbon dioxide balances, and ecological footprint. *BioScience* **2005**, *55* (7), 593–602.
(11) Farrell, A. E.; Plevin, R. J.; Turner, B. T.; Jones, A. D.; O'Hare, M.; Kammen, D. M. Ethanol can contribute to energy and environmental goals. *Science* **2006**, *311* (5760), 506–508.
(12) Groode, T. Fueling Vehicles with Ethanol: Calculating Impacts on Energy Use and Emissions. *Energy Environ.* **2006**, *2*, 4–6; http://lfee.mit.edu/public/e&e_October_2006.pdf.
(13) Lavigne, A.; Powers, S. E. Evaluating fuel ethanol feedstocks from energy policy perspectives: A comparative energy assessment of corn and corn stover. *Energy Policy* **2007**, *35* (11), 5918–5930.
(14) Pimentel, D.; Patzek, T. W. Ethanol production using corn, switchgrass, and wood; Biodiesel production using soybean and sunflower. *Nat. Resour. Res.* **2005**, *14* (1), 65–76.
(15) Shapouri, H.; Duffield ; Wang, M. *The Energy Balance of Corn Ethanol: An Update*; Argonne National Laboratory: Argonne, IL, 2008; p 20.
(16) Fargione, J.; Hill, J.; Tilman, D.; Polasky, S.; Hawthorne, P. Land clearing and the biofuel carbon debt. *Science* **2008**, *319* (5867), 1235–1238.
(17) *Water Implications of Biofuels Production in the United States*; National Research Council; National Academies Press: Washington, DC, 2008; p 88.
(18) King, C. W.; Webber, M. E. Water Intensity of Transportation. *Environ. Sci. Technol.* **2008**, *42* (21), 7866–7872.
(19) Chapagain, A. K.; Hoekstra, A. Y. A. *Water Footprints of Nations, Volume 1*; UNESCO-IHE: Paris, 2004.
(20) *Energy Demands on Water Resources; Report to Congress on the Interdependency of Energy and Water*; U.S. Department of Energy: Washington, DC, 2006; p 80.
(21) *Biomass to Chemicals and Fuels: Science, Technology and Public Policy; Energy Forum*; Baker Institute: Houston, TX, 2008; p 129.
(22) Hutson, S. S.; Barber, N. L.; Kenny, J. F.; Linsey, K. S.; Lumia, D. S.; Maupin, M. A. *Estimated Use of Water in the United States 2000*; U.S. Geological Survey: Reston, VA, 2004.
(23) *USDA 2008 Acreage Report*; National Agriculture Statistics Service, U.S. Department of Agriculture: Washington, DC, June 2008; p 41.
(24) Nebraska appeals ruling against Republican River taxes; www.uswaternews.com/archives/arcrights/8nebrappe6.html.
(25) Mcguire, V. L. *Ground Water Depletion in the High Plains Aquifer*; Fact Sheet 2007-3029; U.S. Geological Survey: Reston, VA, 2007.
(26) *USDA Forecasts Robust Corn and Soybean Crops, Despite Flooding*; National Agriculture Statistics Service, U.S. Department of Agriculture: Washington, DC, August 2008.
(27) Karl, T. R.; Meehl, G. A.; Miller, C. D.; Hassol, S. J.; Waple, A. M.; Murray, W. L. *Weather and Climate Extremes in a Changing Climate*; U.S. Climate Change Science Program: Washington, DC, 2008; www.climatescience.gov.
(28) Galloway, J. N.; Aber, J. D.; Erisman, J. W.; Seitzinger, S. P.; Howarth, R. W.; Cowling, E. B.; Cosby, B. J. The nitrogen cascade. *BioScience* **2003**, *53* (4), 341–356.
(29) Rabalais, N. N. Nitrogen in aquatic ecosystems. *Ambio* **2002**, *31* (2), 102–112.
(30) *Hypoxia in the Northern Gulf of Mexico*; EPA-SAB-08-003; U.S. Environmental Protection Agency: Washington, DC, 2008.
(31) *Conservation Reserve Program: Summary and Enrollment Statistics*; National Agriculture Statistics Service, U.S. Department of Agriculture: Washington, DC, 2008; p 8.

(32) Powers, S. E. Nutrient loads to surface water from row crop production. *Int. J. Life Cycle Assess.* **2007**, *12* (6), 399–407.

(33) ‘Dead Zone’ Again Rivals Record Size 2008; Louisiana Universities Marine Consortium (LUMCON); www.gulfhypoxia.net/research/shelfwidecruises/2008/PressRelease08.pdf.

(34) *Hypoxia in the Gulf of Mexico Studies*; U.S. Geological Survey: Reston, VA, 2008; http://toxics.usgs.gov/hypoxia/.

(35) Mississippi River/Gulf of Mexico Watershed Nutrient Task Force. *Action Plan for Reducing, Mitigating, and Controlling Hypoxia in the Northern Gulf of Mexico*; U.S. Environmental Protection Agency: Washington, DC, 2001; p 36; www.epa.gov/msbasin/pdf/actionplan2001.pdf.

(36) Donner, S. D.; Kucharik, C. J. Corn-based ethanol production compromises goal of reducing nitrogen export by the Mississippi River. *Proc. Nat. Acad. Sci., U.S.A.* **2008**, *105* (11), 4513–4518.

(37) Sylvan, J. B.; Dortch, Q.; Nelson, D. M.; Maier Brown, A. F.; Morrison, W.; Ammerman, J. W. Phosphorus limits phytoplankton growth on the Louisiana shelf during the period of hypoxia formation. *Environ. Sci. Technol.* **2006**, *40* (24), 7548–7553.

(38) Goolsby, D. A.; Battaglin, W. A.; Aulenbach, B. T.; Hooper, R. P. Nitrogen flux and sources in the Mississippi River Basin. *Sci. Total Environ.* **2000**, *248* (2−3), 75–86.

(39) Burkart, M.; James, D.; Liebman, M.; van Ouwerkerk, E. Integrating principles of nitrogen dynamics in a method to estimate leachable nitrogen under agricultural systems. *Water Sci. Technol.* 2006*53*, 289–301.

(40) Powers, S. E.; AscoughL. A.; Nelson, R. G. Soil and Water Quality Implications Associated With Corn Stover Removal and Herbaceous Energy Crop Production in Iowa; In *Proceedings of the 2008 Annual International Meeting of the American Society of Agricultural and Biological Engineers*; Providence RI, 2008; paper number 083916.

(41) *Biofuels and the Bay: Getting It Right To Benefit Farms, Forests and the Chesapeake*; Chesapeake Bay Commission: Annapolis, MD, 2007.

(42) Parrish, D. J.; Fike, J. H. The biology and agronomy of switchgrass for biofuels. *Crit. Rev. Plant Sci.* **2005**, *24* (5−6), 423–459.

(43) *National Statistics: Corn, Field.* National Agricultural Statistics Service: Washington, DC, August 2009; www.nass.usda.gov/QuickStats/index2.jsp.

(44) *CRP Contract Summary and Statistics*; U.S. Department of Agriculture: Washington, DC, August 2009; www.fsa.usda.gov/FSA/webapp?area=home&subject=copr&topic=landing.

ES802162X