Environmental Science & Technology
Policy Analysis
pubs.acs.org/est

Regional Water Implications of Reducing Oil Imports with Liquid Transportation Fuel Alternatives in the United States

Sarah M. Jordaan,*[†,‡,§] Laura Diaz Anadon,[†] Erik Mielke,[†] and Daniel P. Schrag[§]

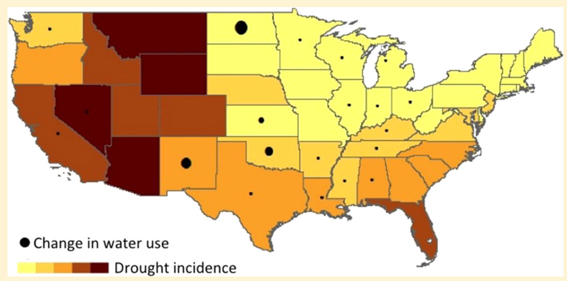
[†]Belfer Center for Science and International Affairs, John F. Kennedy School of Government, Harvard University, 79 John F. Kennedy Street, Cambridge, Massachusetts 02138, United States

[‡]Department of Political Science, University of Calgary, 2500 University Drive NW, Calgary, Alberta, Canada T2N1N4

[§]Department of Earth and Planetary Sciences, Harvard University, 20 Oxford Street, Cambridge, Massachusetts 02138, United States

Supporting Information

ABSTRACT: The Renewable Fuel Standard (RFS) is among the cornerstone policies created to increase U.S. energy independence by using biofuels. Although greenhouse gas emissions have played a role in shaping the RFS, water implications are less understood. We demonstrate a spatial, life cycle approach to estimate water consumption of transportation fuel scenarios, including a comparison to current water withdrawals and drought incidence by state. The water consumption and land footprint of six scenarios are compared to the RFS, including shale oil, coal-to-liquids, shale gas-to-liquids, corn ethanol, and cellulosic ethanol from switchgrass. The corn scenario is the most water and land intense option and is weighted toward drought-prone states. Fossil options and cellulosic ethanol require significantly less water and are weighted toward less drought-prone states. Coal-to-liquids is an exception, where water consumption is partially weighted toward drought-prone states. Results suggest that there may be considerable water and land impacts associated with meeting energy security goals through using only biofuels. Ultimately, water and land requirements may constrain energy security goals without careful planning, indicating that there is a need to better balance trade-offs. Our approach provides policymakers with a method to integrate federal policies with regional planning over various temporal and spatial scales.



1. INTRODUCTION

Since the oil crisis in the 1970s, energy security has been a long-standing concern of policymakers in the United States. This concern continues as 57% percent of crude oil processed in U.S. refineries was imported in 2012.[1] The United States' continued reliance on oil keeps the questions about the economic consequences of energy imports and the associated vulnerability of the U.S. to politically motivated energy supply disruption in the minds of the policymakers. The desire to achieve energy security was underscored in the March 2011 speech where President Obama announced a new U.S. a goal to reduce the ten million barrels of oil imported a day by one-third by 2025.[2] The mix of policies that is expected to contribute toward this goal are increasing the efficiency of the vehicle fleet; increasing electrification; increasing domestic petroleum production; and substituting petroleum-based fuels with biofuels. Among the most prominent of these policies to date, the renewable fuel standard (RFS), was passed under the Energy Independence and Security Act of 2007. The RFS mandates an increase in the use of biomass-based fuels from 9 billion gallons in 2008 to 36 billion gallons by 2022.[3−7] Out of those 36 billion gallons, no more than 15 billion are meant to be produced with corn grain, while the remaining 21 billion would be produced from "advanced biofuels" (no less than 16 billion of which should come from cellulosic biofuels, mainly from switchgrass and crop residues).[8] The adequacy of this policy has been questioned because of the many uncertainties associated with both life cycle greenhouse gas emissions and the speed of technological change.[9,10] While biofuels are often discussed in policy, due mainly to their perceived environmental benefits, they are not the only alternative for meeting U.S. energy security goals. Recent increases in shale oil and gas reserves have altered the outlook for America's energy system, switching the focus from importing crude oil and liquefied natural gas to a focus on increasing the domestic energy supply. For example, natural gas can be converted to gasoline or can be used in compressed natural gas vehicles (CNG).[11] Increasing the electric vehicle fleet can also significantly reduce the demand for oil imports. Though technologically viable, the compressed natural gas and transport electrification options necessitate major changes in the vehicle fleet and/or distribution infrastructure.[12] Improving fuel economy is another prominent policy that could be used to reduce transportation emissions. While our analysis did not include an investigation of improved fuel economy, it does rely on the EIA's *Annual Energy Outlook 2011*, which does include improvements in fuel economy in their scenarios. More recently, a standard has been introduced which will result in

Received: March 27, 2012
Accepted: September 18, 2013
Published: September 18, 2013

an increase of fuel economy to the equivalent of 54.5 mpg for cars and light-duty trucks by Model Year 2025.[13] While not included in this analysis, it should be noted that such programs will help to reduce oil consumption by an estimated 2 million barrels per day.

In this paper, we consider the regional water and land-use implications of reaching corn and cellulosic ethanol goals stated in the RFS and compare them to the implications of other liquid-fuel alternatives for reducing oil imports. Of all the alternatives for reducing oil imports, we have chosen to examine liquid transportation fuel options that can be used without making large changes to either the fleet or the distribution infrastructure. These alternatives include (1) a baseline corn-to-ethanol scenario that assumes that the RFS is not implemented, that corn ethanol contributes 10% of the transportation fuel demand in 2022, and that any additional oil required for growth is imported; (2) a business-as-usual scenario where the RFS is not implemented, no oil is imported, and domestic shale oil is produced instead of the RFS; (3) a scenario where cellulosic and corn grain ethanol goals of the RFS are met; (4) a scenario where cellulosic ethanol is not commercial and the RFS standards are met only with ethanol from corn grain; (5) a switchgrass-to-ethanol scenario that assumes that breakthroughs in switchgrass conversion technologies will enable rain-fed switchgrass crops to meet both the corn and switchgrass RFS goals; (6) a scenario where the RFS is not implemented and coal-to-liquids are produced instead of the RFS; and (7) a shale gas to gasoline scenario that meets the demand that will otherwise be met with the RFS. To the best of the authors' knowledge, there has not yet been any in-depth examination of the consumptive water impacts for shale oil and shale gas transportation fuel options. To understand the regional water implications of each scenario, we make estimates of future water consumption for extraction/farming and conversion at the state-level, and compare them to the industrial and agricultural withdrawals and to the drought incidences.

Previous work related to increased U.S. biofuel production was focused on evaluating the economic and job creation impacts of large increases in the role of biofuels in reducing U.S. oil dependence,[14,15] and thus did not focus on water and land-use implications. Other studies have quantified current direct average water intensity (defined as consumption and withdrawal) related to the production of various types of transportation fuels in the United States,[16] but did not use scenarios or spatially resolved information to estimate the potential impacts of various policies promoting those fuels. The lack of integration of spatial data has been identified not only as a key limitation to life cycle assessment (LCA),[17,18] but, more specifically, as a limitation for the application of LCA to biofuels. Indeed, the incorporation of spatially resolved information was one of the seven grand challenges in the LCA of biofuels identified in the 2011 meetings of the Life-Cycle Program of the Energy Biosciences Institute at the University of California, Berkeley.[19] Other recent work compares the water footprint of gasoline from conventional oil and oil sands with that of first generation and cellulosic ethanol and identifies what fraction of current water consumption takes place in drought-prone areas.[20] While Scown et al. (2011) use a drought index to indicate what fraction of current corn to ethanol, cellulosic ethanol from miscanthus, oil sands to gasoline, and crude oil to gasoline comes from drought prone areas, it does not estimate the impacts of a prominent policy into the future or discuss how these impacts may be mitigated with other possible alternatives to reduce oil imports (e.g., coal-to-liquids, shale gas-to-liquids, or shale oil-to-liquids). Using current designs, we estimate the amount of motor vehicle fuels that can be displaced by other fuels using gallon of gasoline equivalents (GGE) metrics. As a result, we include the GGE of gasoline, ethanol, and diesel. We use this approach to be consistent with policy for replacing motor vehicle fuels. Previous studies have characterized water consumption and withdrawal for different liquid fuels in terms of intensity. Although none have characterized shale gas and shale oil specifically, it is important to understand total water requirements to place potential impacts in a regional perspective.

2. MATERIALS AND METHODS

In this work, we focus specifically on the extraction and conversion phases of the life cycle of fuel production technologies with a process-based approach focused on the inclusion of spatially resolved data into LCA. In this analysis we neglect the consideration of water used in several ways: (1) to transport the feedstock from mines or farms to refineries; (2) to transport refined fuel to the point of sale to consumers; and (3) where the water use is embedded in the manufacture and installation of physical equipment (see King and Webber).[13]

As we detail in the description of the assumptions made for each scenario, the projected spatial allocation of water consumption is based on the most likely evolution of extraction, farming, and conversion facilities given the information available today. While it is clearly impossible to predict how the scenarios would unfold given changes in cost and political realities in the future, the general trends reported are meaningful in that they provide a sense of where the largest water stresses are likely to be found (and, approximately, how large they may be) depending on what fuels are considered to replace oil imports in an RFS context. Water withdrawal is defined as the amount of water removed from the ground or diverted from a water source for use. While there is some debate surrounding exactly which metric should be used,[21−27] we define water consumption as the difference between the water withdrawn from surface water and the water consumed in evaporation, evapotranspiration, and product integration, discharge to the sea, or percolation to the salt sink (thus not re-released into the waterbody). For biofuels, this will include irrigation rather than evapotranspiration. We quantify consumptive water use for each scenario rather than withdrawal. Water consumption for each scenario is then normalized to water withdrawals for irrigation and for industrial use. Recent consumption data is not available from the U.S. Geological Survey (USGS); therefore we use water withdrawals to obtain conservative estimates for the relative change in water requirements.

For each scenario, a variety of assumptions were used to characterize the expected regional fuel production and its corresponding land use and water consumption. The RFS would require an additional 3.0 billion gasoline gallon equivalents (GGE) of corn ethanol and 10.8 billion GGE of cellulosic ethanol, if cellulosic ethanol were commercial, amounting to a total of 13.8 GGE. In our RFS scenario, we examine the maximum amount of cellulosic ethanol to be produced. For the scenarios that incorporate corn ethanol production, corn yields and irrigation by state were derived from USDA data.[28] It was assumed that yields increase at a rate of 1% per year up to 2022, which is consistent with historical increases in yield.[29] In the Supporting Information, we test the sensitivity of the results by varying the crop yield from −4% to 4%. Dry milling, which accounts for 80% of corn ethanol production in the U.S. today, was assumed to be the key conversion process. Water consumed for corn conversion was allocated by state according to the current location of corn biorefineries as per data from the Renewable Fuels Association.[30] Corn crops are expected to replace soy, which is currently not used for fuel production, with the expansion of the biofuel industry.[31] Water consumed by displaced crops was defined as the difference between the water consumed per acre of soy and the water consumed per acre of corn.[32] Water was allocated to coproducts (dried distillers grain) based on energy content.[33]

To provide a lower bound for water consumption of ethanol production, rain-fed switchgrass was used for the cellulosic ethanol case. The amount of land available for rain-fed switchgrass by state was used to determine the spatial distribution of production. The allocation of switchgrass crop by state was based on POLYSYS model results from a 2006 study from the University of Tennessee[12] in which they estimated the feasibility of a vision to produce 25% of U.S. motor vehicle fuels and 25% of U.S. electric power by 2025 with biomass. POLYSYS provides annual estimates of changes in land-use resulting from the demand generated by bioenergy industries (including switchgrass production), and changes in economic conditions that affect adjustment costs. Conversion factors from switchgrass to gallons of ethanol (or equivalent) for biochemical and thermochemical pathways were taken from Wu et al. (2009).[34] Biochemical conversion relies on either acids or enzymes to break down the lignins followed by fermentation. Thermochemical conversion typically relies on gasification followed by Fischer−Tropsch processes to convert the syngas to liquids, but may also involve a combination of pyrolysis, hydrotreating, and hydrocracking.[35,36]

We estimate natural gas (NG) production equivalent to approximately 3 tcf/year is required to produce 13.8 gallons of gasoline. Natural gas data on drilling and production were extracted from HPDI, an oil and gas database.[37] Future production of shale gas by play is assumed to grow proportionally to current production by play. The water consumed by year was calculated using the number of wells drilled thereby assuming that the timing of the water injected for hydraulic fracturing is related to well completion and refracturing is minimal in comparison. In shale gas development, the vast majority of water consumed per well takes place in the first two weeks of drilling. There is a clear downward trend at the play level in the water intensity of shale gas production over time after plays come online, likely driven by the improved recovery through learning as well as by the accumulation of producing wells and subsequent increases in cumulative production that do not depend on large injections of water. To determine the amount of water injected for shale gas extraction in 2022, the intensity was projected using the trend of the Barnett shale, which is the oldest active shale play and is expected to have significant growth. Recycled and reused water was assumed to range between 0% and 50% of the water consumed for hydraulic fracturing with an average of 25%, which may comprise of flowback water from the well in question or other treated water from other operations. Literature values we found ranged from 0% when produced water is injected[38] to 45%.[39] We chose an aggressive range in order to demonstrate improvements in water reuse and recycling that may occur moving forward. In addition, this analysis relies on relative order of magnitude estimates, diminishing the need for detailed sensitivity analyses, as the conclusions will not be changed. Land use was quantified for extraction, but that used for building natural gas-to-liquids (GTL) plants was assumed to be negligible. Land footprint was estimated per well from an existing study[40] and was converted to an annual spatial requirement for the natural gas production required to meet the scenario. Three different configurations of Fischer−Tropsch processes were used to estimate the potential water consumed for the GTL conversion, where water is used primarily in the steam methane reforming and in the water gas shift reaction.[41] It was assumed that water for the GTL process was consumed in the Petroleum Administration for Defense District (PADD) in which the natural gas was extracted. The water was then allocated to states according to current refining capacity in each state based on the underlying assumption that building plants near refineries would provide access to various types of infrastructure, for both process inputs and gasoline distribution.

The study's coal-to-liquids (CTL) scenario projected coal production equivalent to 330−380 million additional tonnes of coal mined per year to produce 13.8 gallons of gasoline. Bituminous and subbituminous coal mining data reported by the U.S. Energy Information Administration (EIA) was used to characterize coal production by state. The water consumed by year for coal mining was calculated using previous estimates of the water intensity of coal.[42] Land use was quantified for extraction, but that used for the CTL plant was assumed to be negligible. Four different configurations of the Fischer−Tropsch process were used to estimate potential water consumed for CTL conversion, where water is used primarily in autothermal reforming and the water gas shift reaction.[28] Three of four CTL designs considered utilize bituminous coal while the fourth design considered utilizes subbituminous coal. For the scenario used in the geospatial analysis, the current proportion of bituminous and subbituminous coal production in 2010 was used for projecting the type of coal produced. The average of the three designs was used for the bituminous coal, with the underlying assumption that each would be as economically viable as the other. It was assumed that water for conversion was consumed in the PADD in which the coal was mined. The water was then allocated to states based on refining capacity based on the same reasoning used in the GTL case.

The study's shale oil scenario estimates 2022 oil production equivalent to 0.45 billion bbls/year allocated by states to produce 13.8 billion gallons of gasoline equivalent. Data were extracted from HPDI on drilling and production. Similar to the shale gas case, the water consumed by year was calculated using the number of wells drilled annually, assuming the timing of water injected in hydraulic fracturing is related to well completion and refracturing is minimal in comparison. Trends for the water intensity of shale oil from the main plays (Bakken, Eagleford, Bone-Spring, and Monterey)[43] did not show a steady downward trend as with shale gas. As a result, water intensity was calculated as the average water intensity of shale oil extraction over the past decade for all of the plays considered. The same amount of water recycled for shale gas was assumed for shale oil extraction. The methodology for allocating water consumed in refining was similar to that of GTL, by assuming water is consumed in the PADD in which the oil is extracted,

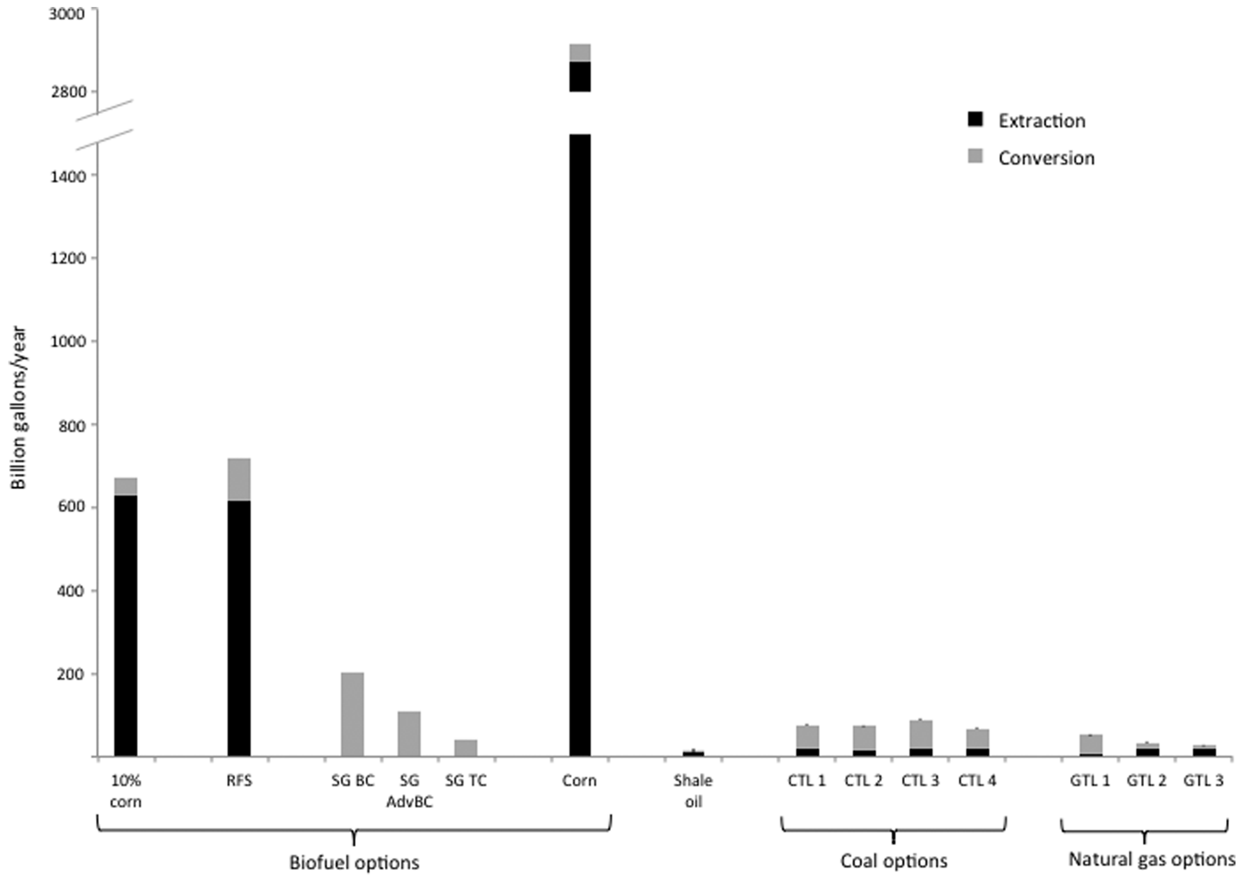


Figure 1. U.S. consumptive water use of each scenario in billion gallons in 2022. For clarity, the scenarios are presented in the following order: baseline, renewable fuel standard (RFS), switchgrass using biochemical conversion (SG BC), switchgrass using advanced biochemical conversion (SG AdvBC), switchgrass using thermochemical conversion (SG TC), corn using dry milling (Corn), shale oil, four configurations of coal-to-liquids options (CTL 1−4), and three configurations of natural gas to liquids (GTL 1−3). The error bars show the variation in estimates from recycling of water, demonstrating little change in the overall magnitude.

and then allocated to states by refining capacity.[44] Water is allocated to coproducts on an energy content basis, using a method that is based on the average product slates from 2010 to 2011 in the refinery yields provided by the EIA.[45] The amount of land disturbed per shale oil pad was assumed to be the same as that for shale gas per well[27] and intensity was determined using annual oil production to meet the scenario's goals as the same infrastructure is required and the operations are similar.

To place the water requirements in perspective, water consumption of each scenario was compared to USGS data on water withdrawals of industrial and agricultural sectors by state[46] using a simple ratio. Since USGS data for consumption is not available for recent years, water withdrawals are used as a conservative comparison as withdrawals are always higher than consumptive uses are. We refer to this as the consumption to withdrawal ratio (CWR). Increases in water consumption are less likely to be problematic in areas where water is abundant than in areas where water availability is constrained. Due to the limited amount of integrated, large-scale spatial data on water flow and demand at the local level, we employ a simpler approach by using drought incidence by state as a proxy.[17] Data on the Palmer Drought Index from 2000 to 2010 were downloaded by state.[47] It is well-known that available technology and science has limited ability to forecast specific drought beyond a few months in advance for a region.[48] Rather than using longer or older data sets, we chose the past decade to capture more recent trends. We do not aim to predict drought occurrence or severity, but rather to provide an indication of recent drought incidence. Drought incidence was calculated as the percentage of time that a state experienced severe, extreme, or exceptional drought. These data were then exported to ArcGIS to create a shapefile where maps were created overlaying future water consumption for each scenario divided by current water withdrawals (industrial and agricultural) and drought by state.

The sensitivity of the results to changes in switchgrass conversion technologies, CTL configurations, and GTL configurations was tested as well as the effects of varying water recycling and reuse in the recovery of hydrocarbons from shale gas and oil formations. With the exception of switchgrass, these sensitivity analyses were typically did not lead to substantial changes in the results. An additional suite of scenarios was developed to test the sensitivity of the results to the total overall production of oil substitutes. These scenarios can be found in the Supporting Information, where we examine the water and land implications of reaching the goal of reducing U.S. oil imports by one-third by 2025, outlined by President Obama in March 2011, using the conventional oil substitutes considered.

3. RESULTS

As shown previously,[20] corn ethanol produced using dry milling has significantly greater water consumption than other liquid

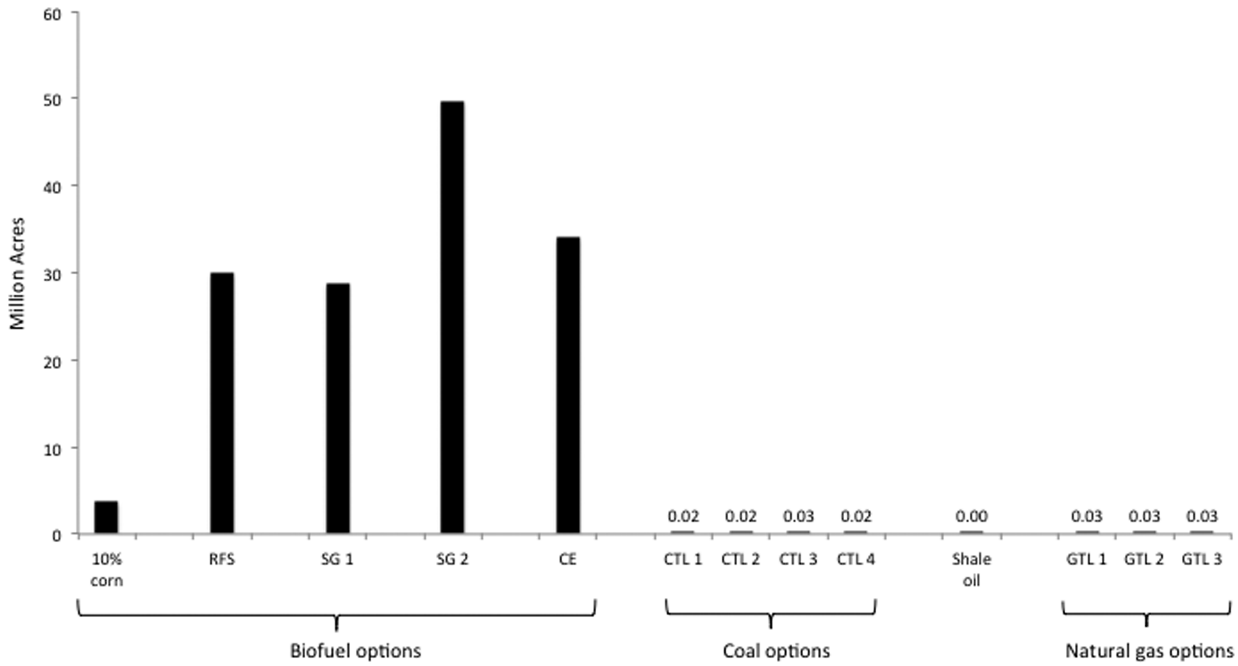


Figure 2. Land use for each scenario in million acres. The scenarios are presented in the following order: baseline, renewable fuel standard, switchgrass using estimates for improved yields (SG1) and current yields (SG2), corn ethanol (CE), shale oil, four configurations of coal-to-liquids (CTL 1−4), and three configurations of natural gas to liquids (GTL 1−3). Fossil fuel options are orders of magnitude smaller than biofuel options.

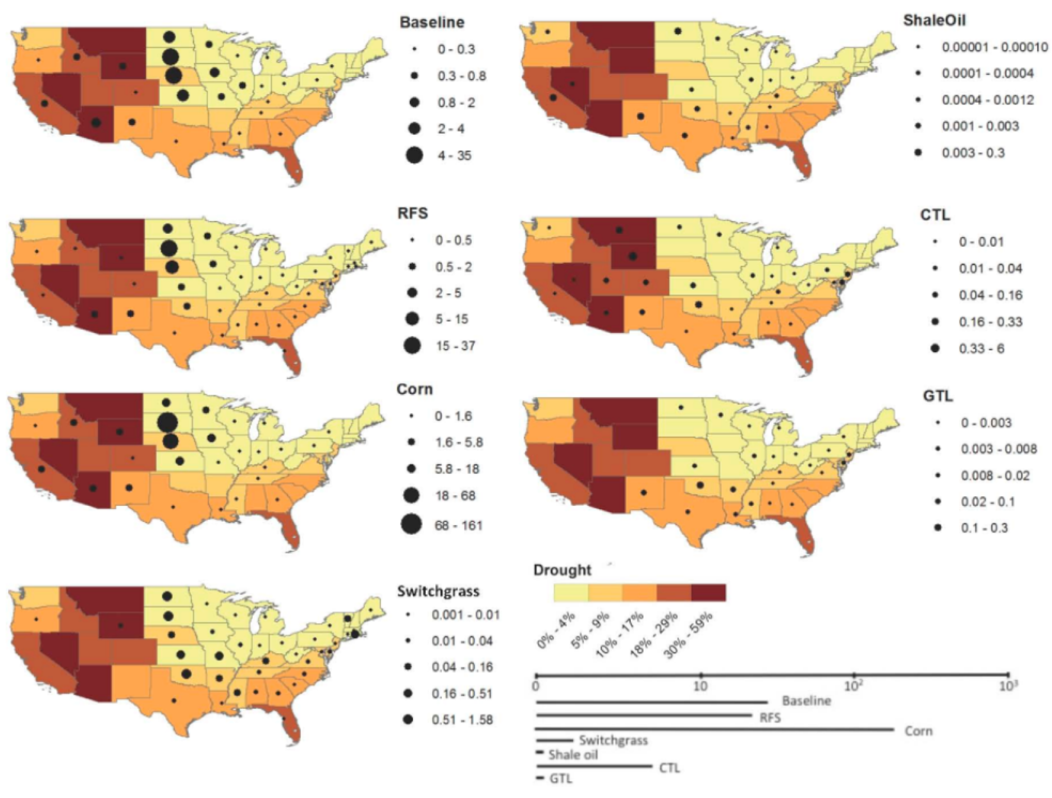


Figure 3. The ratio of annual water consumption for each scenario in 2022 to industrial water withdrawals by state in 2005 is depicted by the circles. To demonstrate the relative magnitude of the ratio by state, we include a legend for reference. Drought incidence is shown for each state with darker colors demonstrating a higher percentage of time spent in drought.

transportation options, primarily due to the irrigation of crops (Figure 1). If cellulosic ethanol becomes commercial, it could have a much lower consumptive water use, particularly if it was produced using rain-fed switchgrass in concert with thermochemical conversion, reaching water consumption levels on the order of those of fossil fuel options. While Figure 1 demonstrates a comparison of irrigated water, when evapotranspiration is considered, rain-fed switchgrass requires 1401 L of water per liter of ethanol compared to corn that requires 1262 L of water per liter of ethanol.[21] A key finding of this

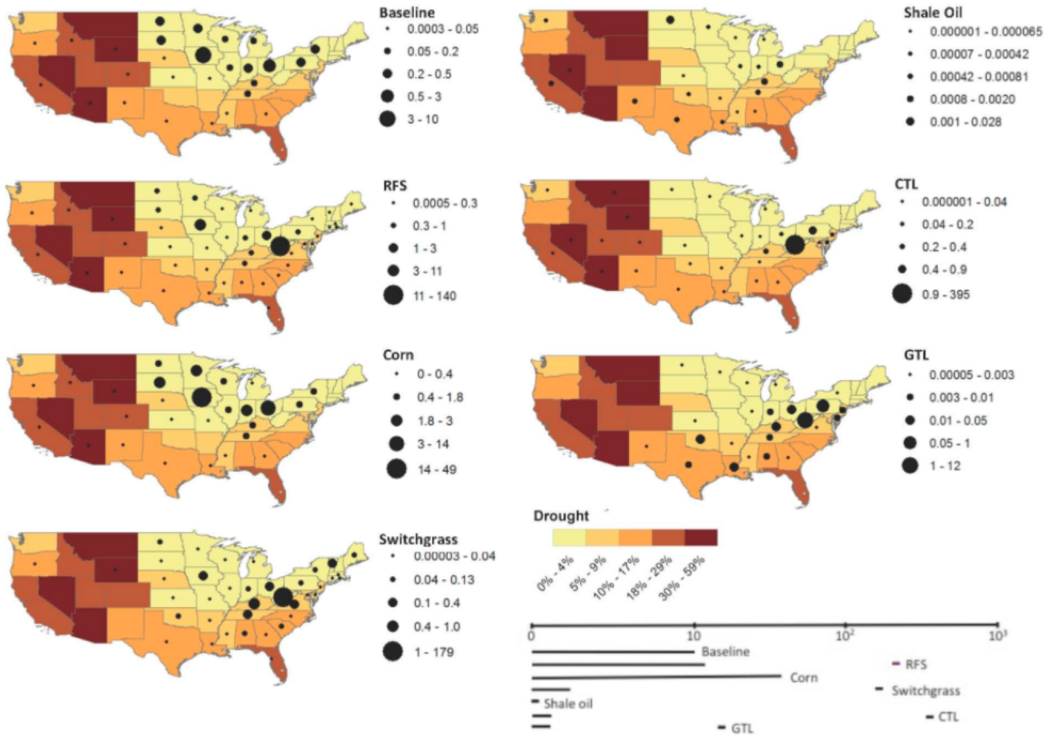


Figure 4. The ratio of annual water consumption for each scenario in 2022 to irrigation water withdrawals by state in 2005 is depicted by the circles. To demonstrate the relative magnitude of the ratio by state, we include a legend for reference. Drought incidence is shown for each state with darker colors demonstrating a higher percentage of time spent in drought. It should be noted that WV has very low water withdrawals for irrigation, resulting in a seemingly high ratio.

analysis is that the baseline option, using anticipated growth in 2022, uses an order of magnitude more water than the fossil fuel scenarios.

The land use of fossil fuels was found to be negligible in comparison to biofuels (Figure 2). The direct land use of shale oil and gas is 4 orders of magnitude smaller than that of first generation biofuel options. When analyzing the impact of the scenarios on land use by state, we focus on the biofuel scenarios as they have a much more significant direct land requirement. In the Supporting Information, we provide the percentage of land required by state for each scenario and demonstrate that to fulfill the goals of the RFS using only first generation biofuel technologies (e.g., corn fermentation), 10–30% of the land in several states would be required under our assumptions. The yield of switchgrass is currently low, resulting in land requirements in cellulosic ethanol scenarios that are greater than those of the corn ethanol scenarios. We show that with aggressive breeding programs, yields may reach levels where land requirements of switchgrass crops may be less than that of corn.

Figures 3 and 4 demonstrate the regional water consumption of each scenario compared to the drought incidence by state. We compare water consumption in all scenarios to industrial water withdrawal (Figure 3) and to irrigation water withdrawal (Figure 4). We discuss the normalized consumptive water use by scenario to current industrial water withdrawals using a consumption to withdrawal ratio (CWR), unless indicated otherwise. Consumptive water use is also normalized to irrigation water withdrawals for the biofuel scenarios for a more relevant comparison. Given the water intensive nature of corn, it is not surprising that the increases in the ratio of water consumption to withdrawal by state in the corn scenario are significant. What should be noted is the high increase of CWR in drought-prone states, particularly in the Rockies and in California. Idaho, Wyoming, New Mexico, and Arizona would see increases in consumptive water use compared to industrial withdrawal ranging from a factor of 1.9 for Idaho to a factor of 5.8 for Arizona, with the rest falling within this range. When we compare new water consumption for corn by state to irrigation withdrawals in these states, the difference is less significant. Of the drought prone states identified above, water use in the corn scenario would result in an increase of consumptive use to withdrawals ranging from 0.3% in WY to 3% in Arizona. The corn scenario results in very large increases compared to irrigation in some states that are not prone to drought; for example, in South Dakota the increase in water consumption is 3-fold compared to current irrigation withdrawals and in Iowa, it is on the order of 48. Though not a drought-prone state, these large increases in water consumption may result in water constraints and in an inability to reach these levels of production.

The GTL scenario decreases water consumption by an order of magnitude compared to water consumption under the baseline scenario. It would also result in water consumption in states that are less drought-prone. Using Arizona as an example, the baseline scenario and the RFS increases water consumption by 1.2 and 1.3 times the current industrial withdrawals respectively, whereas GTL uses none. In Texas, GTL increases consumptive water use by 2% when compared to current industrial water withdrawal, whereas there is a 5% increase under the baseline and RFS scenarios. In New Mexico, GTL results in significantly less water consumption when compared to the baseline and the RFS scenarios. The GTL scenarios result in a 7% increase over current industrial water withdrawal, whereas the latter two scenarios increase by approximately 80% when compared to withdrawals.

CWRs in the CTL and shale oil scenarios, while also on the same order as the GTL scenario, are more heavily weighted toward drought-prone areas. We focus on the comparison to industrial water withdrawal for this scenario. CTL would represent a decrease in water consumption when compared to baseline. The largest increases in water consumption compared to withdrawals occur in drought-prone states, for example, CTL has significantly less water consumption in comparison to the baseline and RFS scenarios in Arizona, California, and Idaho. The most significant difference is in Arizona, where the baseline and RFS resulted in an approximate increase of 1.2 and 1.3 times the current industrial water withdrawal, respectively, whereas the CTL scenario resulted in a much smaller increase of 2%. CTL can result in a significant increase in CWR for drought-prone areas, however. In Wyoming, the baseline and RFS scenarios resulted in increases of approximately 0.5 times, whereas CTL resulted in an over 6-fold increase in water consumption compared to 2005 industrial water withdrawal. While the baseline and RFS scenarios require no additional water consumption in Montana using current assumptions, the CTL scenario would result in an increase of approximately 33% over withdrawals. The key findings for the CTL case is that, although the water consumption is relatively low when compared to withdrawals, the largest increases are in areas more prone to drought.

The switchgrass and shale oil scenarios were found to be the least likely to affect drought-prone states. Switchgrass only represents a 3% increase with respect to industrial water withdrawal in Wyoming. Most notably in the Corn Belt, but also in many drought-prone states, significant water increases result from the corn scenario if cellulosic technologies are not commercial, emphasizing the fact that rain-fed switchgrass to ethanol provides a significantly less water intense alternative. The shale oil scenario results in small water consumption when compared with the other cases as more fuel can be produced with less water. The only drought-prone state where this scenario has a significant increase is in California with an increase of 21%, although this is still lower than the baseline increase of 45% when compared to industrial water withdrawals.

4. DISCUSSION

This life cycle framework, which compares the relative change in CWR with drought data from a regional standpoint, can be used to estimate the possible water implications of federal policies and alternatives to those policies. We demonstrate this analytical tool using seven scenarios of possible fuel alternatives. This framework addresses the need to incorporate spatially resolved information within the life cycle assessment of water resource impacts. Using the scenarios presented in this study, water impacts of the RFS were examined in comparison to alternative options for reducing oil imports for the transportation sector. This can inform policymakers with a strategic overview of regional impacts of the RFS and its alternatives. Supporting previous findings, corn ethanol from dry milling was found to have significantly greater overall water consumption than other liquid transportation options, primarily due to crop irrigation. In the corn scenario, we show high CWR in drought-prone states. The largest increases are in states that are not drought-prone but have a magnitude so great that there may be limitations regardless. From the broadest perspective, cellulosic ethanol can have significant water benefits particularly if produced using rain-fed switchgrass in concert with thermochemical conversion, with levels similar to fossil fuel options. The fossil options were found to have the lowest water footprint, though water consumption of CTL was weighted toward drought-prone states. Shale oil and GTL scenarios could increase water consumption in some drought-prone states; however, the general trends for these two scenarios are that they are weighted toward states that experience lower levels of drought.

Limitations to this analysis include the need to improve methods for quantifying land impacts, the exclusion of cumulative effects and growth of other resource uses, and the uncertain nature of reserves, technological deployment, and commercialization. First, there is a need to improve methods used in quantifying land impacts of energy alternatives.[15] For example, the land footprint of natural gas may appear small but it may also result in extensive habitat fragmentation.[49] We include a scenario in the Supporting Information, which demonstrates that there are likely to be limitations to land availability if oil imports are reduced by one-third and biofuels are the sole supply source. Second, cumulative effects of the growth of different sectors of the economy on overall water consumption and land use are not considered, as the water consumption of each scenario is compared with 2005 water withdrawals. Uncertainties that are not fully explored in our analysis include the commercial availability of cellulosic technologies, the location of deployed GTL and CTL plants, and technological improvements, for example in shale gas and shale oil extraction. Water consumption for all conversion technologies that are not demonstrated commercially in the United States (e.g., GTL and CTL) is estimated using engineering models rather than data on actual commercial production facilities. Finally, the discovery of new reserves, particularly in the area of shale oil, could result in significant changes to the distribution of water consumption for each scenario. It should be noted that whether or not shale oil in California can be extracted economically is still to be determined—this play is currently purported to have significant reserves,[30] yet production is still low. As the reserves in the Bakken play are highly uncertain, we include a scenario where production by play in 2022 is proportional to production by play today (as opposed to estimated reserves) in the Supporting Information.

Topics for future research include refining temporal and spatial resolution, applying constraints to scenarios, and applying similar methods to alternative transportation options not considered in this analysis. While finer scale assessments will be an important component for regional planning, the analysis presented here does serve to highlight areas where in-depth regional planning is likely to be warranted under each scenario. As spatial data sets for water availability and consumption improve, this approach can provide a powerful tool to more precisely identify areas where there could be potential bottlenecks for water availability at smaller spatial scales. An initiative is currently underway that will develop a GIS data set representing water budgets by watershed.[50] Using such data, constraints to energy resource development can be better quantified at smaller scales, allowing policymakers to identify where coordination is most important. A recent study examined six scenarios for cellulosic ethanol from Miscanthus, where life cycle greenhouse gases were quantified under economic, land, and water constraints.[51]

Finally, options requiring large changes to the vehicle fleet or distribution infrastructure may reveal additional limitations and/or opportunities for the future of transportation fuels. Future research could examine how water consumption in these scenarios compares with the other options available to power the transportation sector, such as electric vehicles and compressed natural gas. Compressed natural gas will rely only on upstream water consumed in hydraulic fracturing, which is small when compared to other options. Electrification, while it has been found to have water consumption similar to that of shale oil to liquids, can have water withdrawals on the same order of magnitude as biofuels.[14] A more detailed analysis of electrification should focus on both withdrawals and consumptive use and should include an examination of the trend to heavier reliance on combined cycle gas turbines for electricity generation. Fuel economy is naturally a significant portion of increasing energy security and will continue to play a large role in policy heading into the future.

Our approach is an improvement over aspatial models as it provides policymakers with a tool for planning over various temporal and spatial scales, facilitating a better integration between federal policies with regional planning. For example, those advising the legislative branch should produce such analyses to assist policymakers in strategically managing the regional implications of their policies. While we do not claim these results will predict the exact regional outcome of federal policies, this tool can be used to develop inter- and intrastate strategies to attenuate impacts; for example, strategic placement of new capacity, inclusion of more flexibility in fuel choice to meet policy targets, or use of improved technologies. Future scenarios should be run in concert with federal agencies such as the Department of Energy and the Environmental Protection Agency, and state water managers to determine how to manage regional trade-offs associated with federal energy policy. Informative conclusions can be drawn using current assumptions which can be used to shape the future of fuel production such that stress to water supply can be minimized. Water managers in drought-prone states with large expected increases in water consumption could apply restrictions based on instreamflow needs. As the spatial resolution of data sets on water budgets improve, this framework can provide increasingly significant strategic insight into the possible local impacts inherent to different energy choices, whether or not policy goals can be achieved, and the way in which societal goals can be attained by designing or modifying a policy.

Results of our analysis suggest that there may be significant consumptive water and land impacts associated with energy security goals relying on liquid fuel substitutes derived from biofuels. Due to the inherently local nature of land and water impacts, policy goals must move toward incorporating spatial and temporal considerations at increasingly finer scales. At these finer scales and in future research more broadly, it may be valuable to expand the quantification of consumption to include the additional water consumed through photosynthetic and evapotranspiration processes. While our framework provides policymakers with a consistent approach for understanding the possible regional water- and land-use impacts of a policy, it does not answer the question of how to weigh in different environmental factors (e.g., greenhouse gas emissions versus water consumption and withdrawal versus water quality), which is more of a political decision. The overall goal should be to recognize not only the global goals of attenuating climate change but also the trade-offs with impacts more local in nature, such as those to water and land resources. Water and land requirements may ultimately constrain energy security goals if based on biofuels, indicating a need to better understand and balance environmental trade-offs. Our approach provides but one piece of the puzzle and provides a tool that can allow policymakers to strategically shape the implementation of future transportation fuel production to minimize regional effects.

■ ASSOCIATED CONTENT

Supporting Information

Additional information as noted in the text. This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

*(S.M.J.) E-mail: smjordaa@ucalgary.ca.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We thank researchers from the Energy Technology Innovation Policy Group for their helpful feedback. We also thank Tess Williams for the assistance she provided in the data collection for the shale oil scenario. We are most grateful for the funding received from BP and the Science Technology and Public Policy Program of the Belfer Center for Science and International Affairs at the Harvard Kennedy School of Government, Harvard University. Sarah Jordaan undertook the analysis as a fellow at the Belfer Center and completed the research as Assistant Professor at the University of Calgary.

■ REFERENCES

(1) Frequently Asked Questions, US Energy Information Administration. http://www.eia.gov/tools/faqs/faq.cfm?id=32&t=6.

(2) President Obama Sets Goal to Reduced Imports by One Third, US Department of Energy. http://www1.eere.energy.gov/cleancities/news_detail.html?news_id=16858.

(3) *A USDA Regional Roadmap to Meeting the Biofuels Goals of the Renewable Fuels Standard by 2022*; US Department of Agriculture: Washington DC, 2012; http://www.usda.gov/documents/USDA_Biofuels_Report_6232010.pdf.

(4) Renewable Fuel Standard; Environmental Protection Agency. http://www.epa.gov/otaq/fuels/renewablefuels/index.htm.

(5) *Renewable Fuel Standard (RFS): Overview and Issues*; Congressional Research Service: Washington DC, 2012; http://www.nationalaglawcenter.org/assets/crs/R40155.pdf

(6) *Renewable Fuel Standard, 2010 and Beyond*; Environmental Protection Agency: Washington DC, 2010; http://www1.eere.energy.gov/cleancities/toolbox/pdfs/renewable_fuel_standard_program--2010_and_beyond.pdf

(7) *USDA Biofuels Strategic Production Report*. U.S. Department of Agriculture: Washington DC, 2012; http://www.usda.gov/documents/USDA_Biofuels_Report_6232010.pdf.

(8) Energy Independence and Security Act of 2007. Public Law Section 202, H.R. 6-30 to H.R. 6-37. http://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname=110_cong_bills&docid=f:h6enr.txt.pdf

(9) Searchinger, T.; Heimlich, R.; Houghton, R. A.; Dong, F. Land use change greenhouse gases through emissions from use of U.S. croplands for biofuels increases. *Science* **2008**, *319*, 1238−1240.

(10) O'Hare, M.; Plevin, R. J.; Martin, J. I.; Jones, A. D.; Kendall, A.; Hopson, E. Proper accounting for time increases crop-based biofuels' greenhouse gas deficit versus petroleum. *Environ. Res. Lett.* **2009**, *4* (2), 024001.

(11) *The Future of Natural Gas: An Interdisciplinary MIT Study Interim Report*; Massachusetts Institute of Technology: Cambridge, MA, 2010; web.mit.edu/mitei/research/studies/report-natural-gas.pdf.
(12) Yeh, S. An empirical analysis on the adoption of alternative fuel vehicles: The case of natural gas vehicles. *Energy Policy* **2007**, *35* (11), 5865−5875.
(13) Obama Administration Finalizes Historic 54.5 MPG Fuel Efficiency Standards, the White House. http://www.whitehouse.gov/the-press-office/2012/08/28/obama-administration-finalizes-historic-545-mpg-fuel-efficiency-standard
(14) *Impacts on U.S. Energy Expenditures and Greenhouse-Gas Emissions of Increasing Renewable-Energy Use*. RAND Corporation: Boston MA, 2008; http://www.rand.org/pubs/technical_reports/2008/RAND_TR384-1.pdf
(15) English, B C.; De La Torre Ugarte, D. G.; Jensen, K.; Hellwinckel, C.; Menard, J.; Wilson, B.; Roberts, R.; Walsh, M. *25% Renewable Energy for the United States by 2025: Agricultural and Economic Impacts*; University of Tennessee, Institute of Agriculture, 2006; http://www.agpolicy.org/ppap/REPORT%2025x25.pdf
(16) King, C.; Webber, M. Water intensity of transportation. *Environ. Sci. Technol.* **2008**, *42* (21), 866−7872.
(17) Reap, J.; Roman, F.; Duncan, S.; Bras, B. A survey of unresolved problems in life cycle assessment: Part 1: Goal and scope and inventory analysis. *Int. J. Life Cycle Assess.* **2008**, *13*, 290−300.
(18) Jordaan, S. M. Land and water impacts of oil sands production in Alberta. *Environ. Sci. Technol.* **2012**, *46* (7), 3611−3617, DOI: 10.1021/es203682m.
(19) McKone, T. E.; Nazaroff, W. W.; Berck, P.; Auffhammer, M.; Lipman, T.; Torn, M. S.; Masanet, E.; Lobscheid, A.; Santero, N.; Mishra, U.; Barrett, A.; Bomberg, M.; Fingerman, K.; Scown, C.; Strogen, B.; Horvath, A. Grand challenges for life-cycle assessment of biofuels. *Environ. Sci. Technol.* **2011**, *45*, 1751−1756.
(20) Scown, C. D.; Horvath, A.; McKone, T. E. Water footprint of U.S. transportation fuels. *Environ. Sci. Technol.* **2011**, *45*, 2541−2553.
(21) Pfister et al. Assessing the environmental impacts of freshwater consumption in LCA. *Environ. Sci. Technol.* **2009**, *43*, 4098−4104.
(22) Dominguez-Faus, R.; Powers, S. E.; Burken, J. G.; Alvarez, P. J.. The water footprint of biofuels: A drink or drive issue? *Environ. Sci. Technol.* **2009**, *43*, 3005−3010.
(23) Pfister, S.; Bayer, P.; Koehler, A.; Hellweg, S. Environmental impacts of water use in global crop production: Hotspots and trade-offs with land use. *Environ. Sci. Technol.* **2011**, *45* (13), 5761−5768.
(24) Mishra and Yeh. Life cycle water consumption and withdrawal requirements of ethanol from corn grain and residues. *Environ. Sci. Technol.* **2011**, *45* (10), 4563−4569.
(25) Owens, J. W. Water resources in life-cycle impact assessment: Considerations in choosing category indicators. *J. Ind. Ecol.* **2001**, *5* (2), 37−54.
(26) Bayart, J.; Bulle, C.; Deschênes, L.; Margni, M.; Pfister, S.; Vince, F.; Koehler, A. A framework for assessing off-stream freshwater use in LCA. *Int. J. Life Cycle Assess.* **2010**, *15* (5), 439−453.
(27) Canals, L.; Chenoweth, J.; Chapagain, A.; Orr, S.; Antón, A.; Clift, R. Assessing freshwater use impacts in LCA: Part I—Inventory modelling and characterisation factors for the main impact pathways. *Int. J. Life Cycle Assess.* **2009**, *14* (1), 28−42.
(28) USDA. 2007 CENSUS OF AGRICULTURE, Table 8, 2008, USDA, National Agricultural Statistics. http://www.agcensus.usda.gov/Publications/2007/Online_Highlights/Farm_and_Ranch_Irrigation_Survey/fris08_1_28.pdf
(29) *World Agriculture: Towards 2015/2030: An FAO Perspective; Food and Agrocultural Organization*; Earthscan: London UK, 2003; http://www.fao.org/fileadmin/user_upload/esag/docs/y4252e.pdf.
(30) *Building Bridges to a More Sustainable Future-2011 Ethanol Industry Outlook*; Renewable Fuels Association: Washington DC, 2006; http://www.ethanolrfa.org/page/-/2011%20RFA%20Ethanol%20Industry%20Outlook.pdf?nocdn=1
(31) *Water Implications of Biofuels Production in the United States*, Water Science and Technology Board; National Academies Press. Washington D.C., 2008.
(32) Farm and irrigation survey, Table 28: Estimated Quantity of Water Applied and Primary Method of Distribution by Selected Crops Harvested: 2008 and 2003. US Department of Agriculture, Washington DC, 2012. http://www.agcensus.usda.gov/Publications/2007/Online_Highlights/Farm_and_Ranch_Irrigation_Survey/index.asp
(33) Kim S.; Dale B. E. Allocation Procedure in Ethanol Production System from Corn Grain, *Int. J. LCA*, OnlineFirst, LCA Case Studies, **2002**.
(34) Wu, M.; Mintz, M.; Wang, M.; Arora, S. *Consumptive Water Use in the Production of Ethanol and Petroleum Gasoline*, ANL/ESD/09-1; Argonne National Laboratory, Center for Transportation Research, Energy Systems Division, 2009;
(35) Spieght, J. G. *Synthetic Fuels Handbook*; McGraw-Hill: New York, 2009.
(36) Wu, M.; Mintz, M.; Wang, M.; Arora, S. *Consumptive Water Use in the Production of Ethanol and Petroleum Gasoline*, Report ANL/ESD/09-1; Argonne National Laboratory, Center for Transportation Research, Energy Systems Division, 2009; http://www.transportation.anl.gov/pdfs/AF/557.pdf
(37) HPDI. http://info.drillinginfo.com/category/hpdi-2/
(38) Clark, C. E.; Veil, J. A. Produced Water Vol.s and Management Practices in the United States. United States Department of Energy, Argonne National Laboratory ANL/EVS/R-09/1, 2009. www.evs.anl.gov/pub/doc/ANL_EVS__R09_produced_water_volume_report_2437.pdf
(39) Jiang, M.; Griffin, W. M.; Hendrickson, C.; Jaramillo, P.; Van Briesen, J.; Venkatesh, A. Life cycle greenhouse gas emissions of Marcellus shale gas. *Environ. Res. Lett.* **2011**, *6*, 3.
(40) Jiang, M.; Griffin, W. M.; Hendrickson, C.; Jaramillo, P.; VanBriesen, J.; Venkatesh, A. Life cycle greenhouse gas emissions of Marcellus Shale gas. *Environ. Res. Lett.* **2011**, *6*, 034014.
(41) Marano, J. J.; Ciferno, J. P. *Life-Cycle Greenhouse-Gas Emissions Inventory for Fischer−Tropsch Fuels*; National Energy Technology Laboratory: Pittsburgh, PA, 2001.
(42) Gleick, P. H. Water and Energy. *Annu. Rev. Energy Environ.* **1994**, *19* (1), 267−299.
(43) Review of emerging resources: US shale gas and shale oil plays. Energy Information Administration: Washington DC, 2011; ftp://ftp.eia.doe.gov/natgas/usshaleplays.pdf.
(44) Refinery Capacity Report 2011. Energy Information Administration: Washington DC, 2011; http://205.254.135.24/petroleum/refinerycapacity/ Last accessed March 15 2012
(45) *Refinery Yield*; Energy Information Administration: Washington DC, 2012; http://www.eia.gov/dnav/pet/pet_pnp_pct_dc_nus_pct_m.htm (accessed March 15, 2012)
(46) Kenny, J. F.; Barber, N. L.; Hutson, S. S., Linsey, K. S.; Lovelace, J. K.; Maupin, M. A. *Estimated Use of Water in the United States in 2005*, Circular 1344; U.S. Geological Survey, 2009.
(47) NOAA Satellite and Information Service. 2012. www7.ncdc.noaa.gov/CDO/CDODivisionalSelect.jsp# (accessed March 15, 2012)
(48) www.fas.org/sgp/crs/misc/RL34580.pdf
(49) Jordaan, S. M.; Keith, D. W.; Stelfox, B. Quantifying land use of oil sands production: A life cycle perspective. *Environ. Res. Lett.* **2009**, *4*, 024004.
(50) The National Water Census. US Geological Survey, 2012. http://water.usgs.gov/wsi/index.html. (accessed March 19, 2012)
(51) Scown, C. D.; Nazaroff, W. W.; Mishra, U.; Strogen, B.; Lobscheid, A. B.; Masanet, E.; Santero, N. J.; Horvath, A.; McKone, T. E. Lifecycle greenhouse gas implications of US national scenarios for cellulosic ethanol production. *Environ. Res. Lett.* **2012**, DOI: 10.1088/1748-9326/7/1/014011.

■ NOTE ADDED AFTER ASAP PUBLICATION

The last sentence of the first paragraph in the Introduction section was in error in the version of this paper published October 9, 2013. The correct version published October 15, 2013.