Water Footprint of U.S. Transportation Fuels

Corinne D. Scown[*a], Arpad Horvath[a], Thomas E. McKone[b,c]*

[*]Corresponding Author

[a] Department of Civil and Environmental Engineering, University of California, Berkeley

[b] School of Public Health, University of California, Berkeley

[c] Lawrence Berkeley National Laboratory

Address: 407 McLaughlin Hall, UC Berkeley, Berkeley, CA 94720

Email: corinne.scown@gmail.com

Keywords: Water Use, Groundwater, Surface Water, Transportation Energy, Life-Cycle Assessment, Climate Change, Greenhouse Gases, Renewable Energy, Biofuels, Ethanol, Electricity, Gasoline, Petroleum

Brief: This paper explores the implications of emerging U.S. transportation fuels for water resources, as well as the climate change impacts of increased water use.

Abstract

In the modern global economy, water and energy are fundamentally connected. Water already plays a major role in electricity generation and, with biofuels and electricity poised to gain a

significant share of the transportation fuel market, water will become significantly more important for transportation energy as well. While not suitable for use in policy-making, this research provides insight into the potential changes in water use resulting from increased biofuel or electricity production for transportation energy, as well as the greenhouse gas and freshwater implications. It is shown that when characterizing the water impact of transportation energy, incorporating indirect water use and defensible allocation techniques have a major impact on the final results, with anywhere between an 82% increase and a 250% decrease in the water footprint if evaporative losses from hydroelectric power are excluded. The greenhouse gas impact results indicate that placing cellulosic biorefineries in areas where water must be supplied using alternative means, such as desalination, wastewater recycling, or importation can increase the fuel's total greenhouse gas footprint by up to 47%. The results also show that the production of ethanol and petroleum fuels burden already overpumped aquifers, whereas electricity production is far less dependent on groundwater.

Introduction

Water is necessary to sustain all life. Compared to other substances abundant in the environment, water has a high specific heat capacity (approximately four times that of air), which makes it useful for transporting heat in power generation, industrial, domestic, and commercial applications. Supplying water also requires energy for pumping and treatment (*1*). The connection between energy and water has generated interest in recent years, prompting a number of studies that explore both the water requirements for supplying energy (*2-10*) and energy requirements for supplying water (*1, 7, 11-13*).

If energy use is split into two categories, stationary and transportation, it is clear from the breakdown in reference (*14*) that water already plays a major role in stationary energy production: thermoelectric power generation is responsible for approximately 49% of total freshwater withdrawals in the United States (see the Supporting Information, Figure S1 for complete breakdown). Agriculture and public supply also make up a large fraction of freshwater use in the United States. However, transportation energy has not been nearly as reliant on freshwater thus far. Ninety five percent of transportation energy in the United States comes from petroleum fuels (*15*). Oil extraction and refining make up only a fraction of the mining and industrial sectors, which together are responsible for just 5% of total freshwater withdrawals (*14*). If transportation, which is responsible for approximately one third of total U.S. energy consumption (*15*), were to become more reliant on water-intensive sectors such as power generation and agriculture, there could be significant implications for U.S. freshwater availability. As electricity and biofuels are poised to gain a larger share of the transportation fuel market, this is exactly the transition that is taking place. This paper quantifies (1) the potential change in water use resulting from increased ethanol or electricity production for transportation energy with respect to conventional gasoline, and (2) the greenhouse gas (GHG) and freshwater resource availability implications.

Background

Water Requirements for Transportation Fuel Production

Recent interest in the water requirements for energy production has resulted in a number of studies on water use for transportation fuel production (*3, 4, 6-8, 10, 16-20*). However, all but two of these studies do not go beyond the direct water impacts of feedstock extraction/production and fuel production/refining (as shown in the SI, Table S1). Water use impact assessment is also a critical step that has not been taken in the existing studies. Because a liter of water used in already stressed areas such as Southern California is likely to cause more damage than a liter consumed in more water-rich parts of the country, a life-cycle inventory (LCI) alone cannot reveal which fuels cause the greatest burden on freshwater resources. A comprehensive life-cycle assessment (LCA) should include not only the operational water requirements at each life-cycle stage, but water required for design and planning, construction, operation and maintenance, and decommissioning of the infrastructure, as well as the water embodied in the material and energy inputs, or what is referred to as "virtual water" (*21*). This quantity of water should be translated into a measure of the resulting stress on water resources and these impacts should be properly allocated among the many co-products of fuel production systems.

Because there is an ever-expanding number of potential biofuel feedstocks and conversion technologies, choosing which fuel pathways to analyze can be difficult. Gasoline is the largest single energy source for transportation in the United States, making up 59% of total transportation-related energy consumption (*22*), and ethanol is a likely replacement since it can be combusted in spark-ignited internal combustion engines with only minor alterations to the fuel injection system and can be produced using current technologies. Electricity, although it currently makes up less than 1% of total transportation energy consumption (*15*), is included because it has the potential to gain a much greater market share in passenger transportation as the necessary infrastructure is constructed and prices of plug-hybrid and pure electric vehicles fall, particularly with the support of such programs as the California Zero Emission Vehicle (ZEV) program. In order to capture the variation in electricity mixes around the country, all electricity use is categorized by North American Electric Reliability Corporation (NERC) regions (as discussed in more detail in the SI). Table 1 shows the fuel pathways explored in this paper and the relevant life-cycle phases. Petroleum diesel and its biofuel counterparts were not included in this analysis because diesel represents a smaller share of the transportation fuel market (22%) as compared to gasoline (*22*).

Fuel →	Gasoline		Electricity	Ethanol	
Life-Cycle Phase ↓	Conventional Crude Oil	Oil Sands		Corn Grain	Corn Stover & Miscanthus
Feedstock Production/ Extraction & Pre-Processing	Exploration, drilling, extraction	Oil sands extraction, retorting, upgrading	Extraction and pre-processing of fuels used at power plant	Cultivation of crops	Establishment and cultivation of crops
Refining/ Fuel Production	Petroleum refining	Petroleum refining (of synthetic crude oil)	Electric power generation	Biorefining (conversion to ethanol)	Biorefining (conversion to ethanol)
Storage & Distribution	Transport of crude oil to refinery, transport and storage of gasoline after leaving the refinery	Transport of synthetic crude to the refinery, transport and storage of gasoline after leaving the refinery	Storage, transmission, and distribution of electric power	Transport of feedstock to the biorefinery, transport and storage of ethanol after leaving the biorefinery	Transport of feedstock to the biorefinery, transport and storage of ethanol after leaving the biorefinery
Combustion/ Use	Combustion of gasoline in spark-ignited ICE	Combustion of gasoline in spark-ignited ICE	Use of electric power in EVs or PHEVs	Combustion of ethanol in spark-ignited ICE	Combustion of ethanol in spark-ignited ICE

Table 1: Definition of Life-Cycle Phases for Selected Fuel Pathways

Methodology

Water-Use Metrics

Water use can be an ambiguous metric. Because human activities do not chemically destroy water molecules in the same way that, for example, carbon-based fuels are consumed during combustion, the result of water use is a temporary or permanent redistribution of freshwater resources. For example, the City of Los Angeles diverted large amounts of freshwater from Mono Lake, resulting in a significant reduction in the lake's water level (*23*). In contrast, some withdrawn water is immediately returned to its source, such as water cycled through open-loop cooling systems at thermoelectric power plants. This paper employs the two most common water use metrics: consumption and withdrawals. Withdrawals refer to any freshwater that is temporarily or permanently removed from its source, whereas consumption is limited to water that is not returned to its original watershed in the short term (*24*). Possible fates of consumed water include incorporation into a product such as soft drinks, discharge into seawater, saline water, or a water body in a different watershed, and evaporation. In this paper, both withdrawals and consumption only include freshwater. This is because saline and seawater are not considered to be constrained water resources and are not useful for the vast majority of human needs, although salt-tolerant plants may be used as biofuel feedstocks in the future.

Another distinction is made in this paper between surface water and groundwater use. One type may be more desirable for a particular application than another; for example, groundwater is often more energy-intensive because it must be pumped to the surface from underground aquifers, but also requires less treatment than surface water (*11*). As is discussed in the *Weighting Water Use by Potential Stress* section, the vulnerabilities of surface water and groundwater resources are also different. Groundwater aquifers respond to climatic variations more slowly than surface water resources, and can serve as a buffer during times of low rainfall and humidity (*25, 26*). However, groundwater can also be overpumped and thus depleted over time, and depending on the recharge rate, the aquifer may not recover quickly (*25-27*).

Life-Cycle Inventory

LCA is used herein to determine the supply-chain water use of transportation fuels. As shown in Table 1, the life cycle of transportation fuels can be split into four major phases: feedstock production/extraction and preprocessing, fuel production/refining, fuel transportation and distribution, and combustion. All of the phases except combustion are often referred to as upstream or well-to-tank (WTT). Well-to-wheels (WTW) includes the upstream phases plus the use phase (combustion). After accounting for all of the direct impacts from each of these life-cycle phases, the next step is to follow the life cycle of the inputs for those phases. For example, petroleum refineries require large amounts of electricity, and electricity generation requires water for cooling; electricity generation also requires fuels such as coal, uranium, and natural gas whose extraction and processing phases have their own water footprint. There are three different LCA methods: process-based, economic input-output analysis-based EIO-LCA, and hybrid, which is a combination of the former two and is the approach taken in this research. Descriptions of these methods can be found in (*28*) and (*29*). The hybrid approach to the LCI performed in this paper is based primarily on process data collected from a variety of sources, supplemented with EIO-LCA (*30*). The EIO-LCA water impact vector is documented in (*31*). A detailed list of elements included in the LCI is shown in Table 2, and information on data sources can be found in the SI. One methodological issue that can dramatically change the results of an LCI is co-product allocation. When a process results in multiple non-waste outputs, the inputs and environmental impacts must be somehow allocated among the outputs. Table S8 in the SI shows the major instances where allocation must be used in this research, and which method was chosen.

Pathway	Direct	Electricity Consumption	Primary Fossil Fuels	Chemicals	Construction & Materials	Supply-Chain Agriculture	Supply-Chain Services
Crude Oil to Gasoline	• Injection water • Refinery process/cooling/other water	• Electricity for extraction, transportation, storage, & distribution, & refining	• Crude oil • Residual oil • Diesel • Gasoline • Natural gas • Coal	• Biocide • Surfactant • NaOH • Neutralizer • Inhibitor	• Steel • Concrete • Dust control	• All indirect agricultural NAICS sectors	• All service NAICS sectors
Oil Sands to Gasoline	• Injection & other mining water • Refinery process/cooling/other water	• Electricity for extraction, transportation, storage, & distribution, & refining	• Residual oil • Diesel • Gasoline • Natural gas • Coal	• NaOH • Neutralizer • Inhibitor	• Steel • Concrete • Dust control	• All indirect agricultural NAICS sectors	• All service NAICS sectors
Corn Stover to Ethanol	• Refinery process/cooling/other water	• Electricity for transportation, storage, & distribution, & net input/output for biorefining	• Residual oil • Diesel • Gasoline • Natural gas • Propane	• Fertilizers • Sulfuric acid • Lime • Corn steep liquor • Cellulase • Diammonium phosphate • Ammonia • Cooling water chemicals • WWT chemicals	• Steel • Rubber • Concrete • Dust control	• All indirect agricultural NAICS sectors	• All service NAICS sectors
Miscanthus to Ethanol	• Irrigation water ("high" case only) • Refinery process/cooling/other water	• Electricity for transportation, storage, & distribution, & net input/output for biorefining	• Residual oil • Diesel • Gasoline • Natural gas • Propane	• Fertilizers • Glyphosate • Sulfuric acid • Lime • Corn steep liquor • Cellulase • Diammonium phosphate • Ammonia • Cooling water chemicals • WWT chemicals	• Steel • Rubber • Concrete • Dust control	• All indirect agricultural NAICS sectors	• All service NAICS sectors
Corn Grain to Ethanol	• Irrigation water • Refinery process/cooling/other water	• Electricity for farming, transportation, storage, & distribution, & biorefining	• Residual oil • Diesel • Gasoline • Natural gas • Coal • LPG	• Fertilizers • Pesticides • Herbicides • Sulfuric Acid • Lime • Ammonia • Alpha-Amylase & Glucoamylase • Cooling water chemicals • WWT chemicals	• Steel • Rubber • Concrete • Dust control	• All indirect agricultural NAICS sectors	• All service NAICS sectors
Electricity	• Cooling water • Other plant operations water	• Electricity transmission & distribution line losses	• Diesel • Natural gas • Coal • Uranium*	N/A	• Steel • Rubber • Concrete • Glass • Sand • Silicon • Primary fossil fuels	• All indirect agricultural NAICS sectors	• All service NAICS sectors

*Included in primary fossil fuel category, although not a fossil fuel

Table 2: Scope of Water Use LCI

Weighting Water Use by Potential Stress

Freshwater use can result in a number of different impacts, including increased GHG emissions from pumping and treatment; economic impacts due to insufficient supply for any competing industrial, energy-producing, and agricultural activities; human health effects resulting from shortages of potable water; and damage or loss of aquatic habitats. Reference (*32*) explores a number of watershed-level impact metrics, including the water stress index, water resource damage, ecosystem quality damage, human health impacts, as well as an aggregated damage factor that encompasses resource, ecosystem, and human health damage. However, the data-intensity of this type of analysis is such that it becomes difficult to apply, particularly in LCAs that rely on data that are mostly reported on state, county, and national levels rather than watershed levels. There is a resulting disconnect between life-cycle inventories and impact assessment: none of the detailed life-cycle water use studies go beyond the inventory because time and data constraints make it impossible (*8, 10, 19, 33*). In this paper, a new and simpler, less data-intensive approach is taken, aimed at quantifying GHG emissions from the supply of freshwater and identifying the fraction of water use that occurs in areas where surface and groundwater stress may be exacerbated. The approach used here for gauging relative impacts on surface and groundwater stress can be considered analogous to the splitting of criteria pollutant emissions into urban and non-urban categories as is performed in GREET (*34*). Because an impact assessment with high fidelity to reality is difficult and wrought with uncertainty, many studies simply choose to stop at an LCI, or use a software tool with an opaque method of calculating environmental impacts. The assertion made here is that performing even a simple and transparent impact assessment is favorable to omitting the step altogether.

1. GHG-Intensity of Freshwater Supply

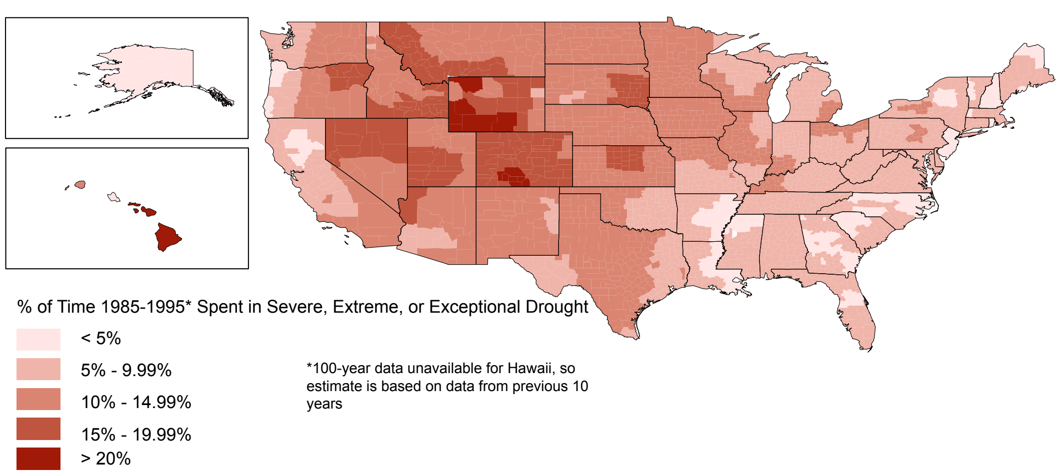
It is well known that climate change can and will impact freshwater resources (*35*), but less frequently acknowledged is the impact of freshwater use on GHG emissions. Raw water pumping from ground or surface water sources, treatment, and distribution all require energy. The GHG-intensity of water varies depending on how far the raw water must be pumped, as well as the extensiveness of treatment and distribution requirements. Agricultural water, for example, is very GHG-intensive in parts of California where at least some water is imported long distances (the State Water Project spans well over 1,000 km); Kern County, CA averages 0.33 grams of CO_2-equivalent emitted per L of irrigation water supplied (see SI Section 4 for supporting calculations). In counties that use local freshwater exclusively, the GHG-intensity is one to two orders of magnitude lower. Because it is assumed that most industrial water, mining/oil extraction water, and power generation cooling water do not require significant treatment, the GHG-intensity is similar to that of agricultural water, altered somewhat by differences in pump efficiencies and fuel types. Public water supply is by far the most energy and GHG-intensive because it must be treated to potable standards and pumped through a distribution system to various customers. In Los Angeles and San Diego Counties, where water is imported long distances, the GHG-intensity is approximately 1 g CO_2e/L water supplied (see SI Table S22), whereas most public water supply in the United States results in approximately 0.5 g CO_2e/L (see SI Section 4). Desalination projects in El Paso County, TX and Hillsborough County, FL also result in an average GHG-intensity of approximately 1 g CO_2e/L.

2. Surface Water Impacts

Surface water, although easily accessed and typically requiring less pumping energy than groundwater, is a vulnerable resource. For example, a period of low or no rainfall can significantly reduce surface water availability. Soil moisture, stream flow, and precipitation all inform drought measurements. The Palmer Drought Index is a common measure of drought severity, which the U.S. Drought Monitor has used to develop five categories: D0: Abnormally Dry, D1: Moderate Drought, D2: Severe Drought, D3: Extreme Drought, and D4: Exceptional Drought (*36*). It is deemed the most effective for measuring impacts sensitive to soil moisture conditions, such as agriculture and has also been used to trigger actions associated with drought contingency plans (*37*). It should be noted that this is not the only popular measure of drought severity. An alternative measure is shown in the Figure S4 of the SI, in which the results are markedly different: the Southeastern United States is highlighted as being the most vulnerable to long-term drought conditions. A map of drought incidence in the United States based on the Palmer Drought Index is shown in Figure 1a. Further details about this rating system are provided in Table S14 in the SI. Although water shortages are typically associated with the arid west, over half of the United States has spent at least 10% of the last 100 years in severe, extreme, or exceptional drought (*36*). For the purposes of this research, areas experiencing drought categorized as D2 or worse for more than 10% of the last 100 years are considered to have elevated drought risk, with the acknowledgment that historical drought data do not necessarily predict future drought vulnerability. Drought incidence data are collected by National Oceanic & Atmospheric Administration (NOAA) climate divisions, which the NOAA then maps to U.S. counties. These county-level data are matched up with county-level surface water withdrawals and consumption LCI data to determine how much surface water is used within drought-prone areas.

3. Groundwater Impacts

One asset of groundwater resources is that they are not as vulnerable to climatic fluctuations as surface water (*25-27*). However, groundwater availability is limited by the recharge rate. If the pump rate exceeds the recharge rate, the aquifer will ultimately be depleted. Additionally, as the water level in unconsolidated aquifers retreats downward, land subsidence can occur. More than 44,000 km^2 of land in the United States is directly affected by subsidence, and of that, approximately 80% is caused by pumping of subsurface water (*38*). No comprehensive national groundwater monitoring system exists (*27*), so mapping groundwater impacts at a local level for the entire United States is not possible. Instead, it is more reliable and useful to focus on susceptible areas that have better monitoring. Twenty seven states have been identified as suffering either significant decline in aquifer levels, subsidence, or both as a result of overpumping, based on information from references (*27*) and (*38*), as shown in Figure 1b. A list of impacts experienced in each state is included in the SI, Table S14. Although the state itself does not experience significant groundwater overpumping impacts, Nebraska is included here because its excessive withdrawals seriously affect groundwater levels in Kansas (*39*). This approach may overestimate groundwater vulnerability, as not all groundwater in each of these states is necessarily threatened. Additionally, increased rainfall and decreased pumping can help some aquifers rebound from previous depletion.



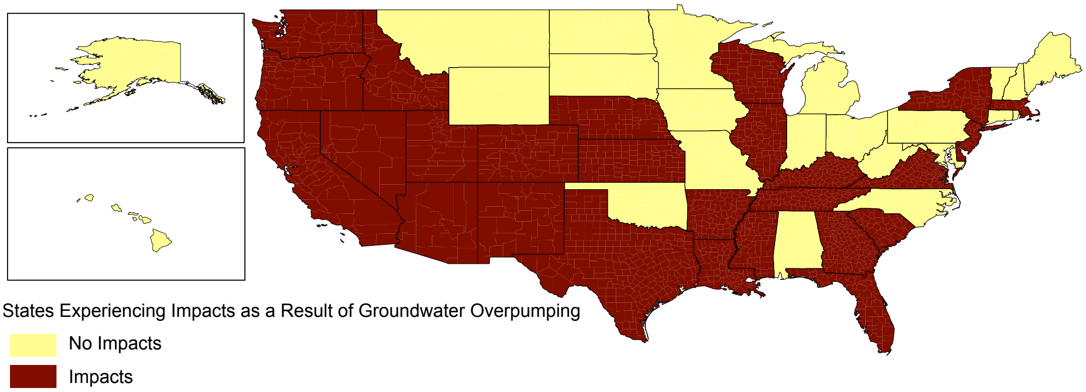


Figure 1a: Drought Incidence in the United States as Defined by Palmer Drought Severity Index (Based on data from reference (*36*))

Figure 1b: Groundwater Overpumping Incidence in the United States

Results

The results are split into two parts: the inventory and the stress-weighted results. As discussed later, the inventory shows that when characterizing the water impact of transportation energy, the addition of indirect water use plus utilization of defensible allocation techniques have a major impact on the final results, with anywhere between an 82% increase and a 250% decrease in the water footprint (see Table 3).

Fuel Pathway	Water Use Metric	% Change
Crude Oil to Gasoline	Consumption	+19%
	Withdrawals	+60%
Oil Sands to Gasoline	Consumption	+26%
	Withdrawals	+82%
Rainfed Corn Grain & Stover to Ethanol	Consumption	+17%
	Withdrawals	+18%
Avg Corn Grain & Stover to Ethanol	Consumption	+3.9%
	Withdrawals	+11%
Miscanthus to Ethanol	Consumption	+28%
	Withdrawals	-250%
U.S. Electricity	Consumption	+17%
	Withdrawals	+11%

Table 3: Percent Change in Water Use Results due to Inclusion of Indirect Water Use

Through exploration of climate change, surface water, and groundwater impacts, we find that placing cellulosic biorefineries in areas where water must be supplied using alternative means, such as desalination, centralized wastewater recycling, or importation can mean up to a 47% increase in the fuel's total greenhouse gas footprint. The production of ethanol and petroleum fuels also places a greater burden on already overpumped aquifers, whereas electricity production is far less dependent on groundwater.

Life-Cycle Inventory

Figures 2a and 2b show the water-use LCI results in terms of withdrawals (W) and consumption (C), broken down by life-cycle phase and major contributor. The results have been normalized by vehicle-km traveled to adjust for the difference in efficiencies of electric vehicles and spark-ignited internal combustion engines, assuming a typical light duty passenger vehicle with a fuel economy of 0.25 km/MJ gasoline (20.5 mpg). A comparable electric vehicle achieves approximately 3.75 times the efficiency (*34*), with a fuel economy of 0.94 km/MJ electricity (3.4 km/kWh). In Figure 2a, average corn grain/stover ethanol clearly stands out as the biggest water consumer although its withdrawals are roughly equal to those of electricity, with crop irrigation making up the majority of its water footprint. While the production-weighted corn irrigation data do include such outliers as AZ and CA, the output from these states is small, resulting in a U.S. average irrigation number that is only 3% higher than that of the top three corn-producing states: IL, IA, and NE (additional data can be found in the SI). Still, it should be noted that the average includes corn produced for purposes other than ethanol such as animal feed, and the water intensity of the marginal unit of corn produced may differ significantly from the average. For non-irrigated crops, the feedstock production phase results in insignificant water use, making refining/fuel production the dominant phase. For petroleum fuels, feedstock extraction and refining are split more evenly. Electricity is also very water-intensive in terms of withdrawals, but the opposite in terms of consumption; electricity consumes less water per km traveled than any other fuel. The feedstock extraction/production phase for electricity (which includes coal mining, natural gas extraction, etc.) is dwarfed by the amount of water required for cooling.

One element of Figure 2b that is treated quite differently among water-use LCIs is the electricity co-product credit for the biomass-to-ethanol (corn stover and Miscanthus) pathway. These biorefineries burn lignin to provide process heat and electricity for the plant, as well as excess electricity that can be sold to the grid. By exporting electricity to the grid, biorefineries essentially become power plants, displacing other electricity production (and its associated water use). Because the withdrawals for average grid electric power generation are so high compared to biorefinery water withdrawals, the electricity co-product credit effectively results in net negative withdrawals (in other words, the withdrawals avoided by the resulting reduction in grid electricity generation are larger than the biorefinery's withdrawals). Also, in both Figures 2a and 2b, the evaporative losses associated with the generation of hydroelectricity are indicated by error bars, with the maximum being 100% allocation of hydro-related impacts to electricity as opposed to water supply, flood protection, and other dam functions. The evaporative losses are a result of the increase in total water body surface area that occurs when a dam is constructed, and are discussed further in reference (*9*).

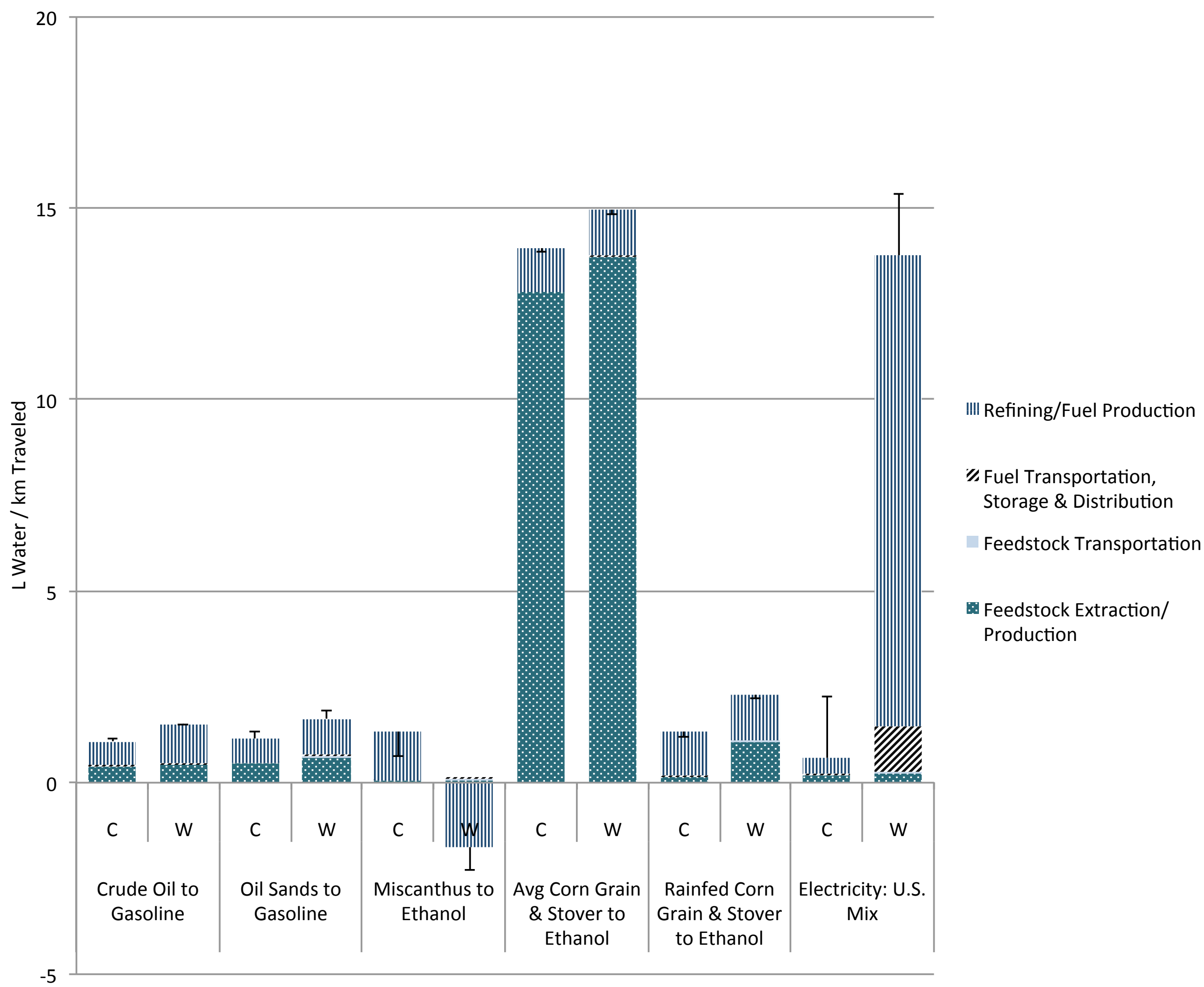
Figure 2b breaks the water footprints down by major contributing factors and tells an even more interesting story. Direct water refers to any water that is used directly for each of the four life-cycle phases (as shown in Figure 2a). As discussed earlier, the vast majority of existing studies on water footprints focus exclusively on direct water use. Figure 2b shows that, particularly for withdrawals, indirect water use can dominate the water footprint. For example, the two most significant factors in total water withdrawals for corn stover to ethanol and Miscanthus to ethanol are chemicals and the electricity co-production credit. Table S11 in the SI shows the percent change in the total water footprint of each fuel pathway as a result of adding indirect water use.

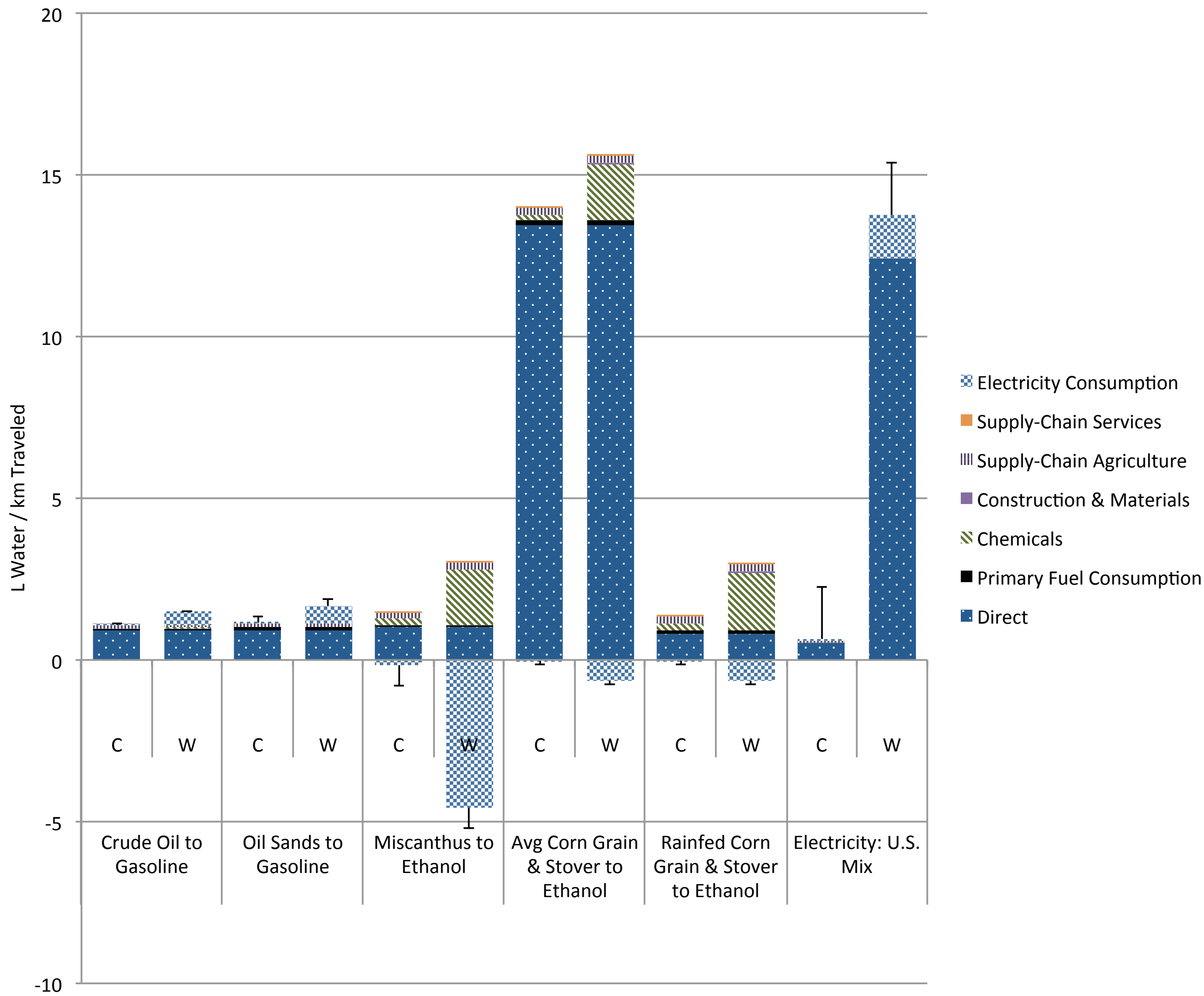
Life-Cycle Inventory Sensitivity Analysis

Using a consequential LCA approach, i.e. analyzing the system at its margin, provides useful information to policy makers who wish to understand the potential consequences of a new mandate, regulation, etc. However, attempting to analyze the marginal impact also introduces a great deal of uncertainty. For example, crude oil consumed in the United States is both produced domestically and imported from foreign countries. So the origin of the marginal barrel of oil (onshore or offshore, domestic or foreign, primary, secondary, or tertiary extraction techniques) depends on market and policy factors that are constantly changing and very difficult to predict. If the marginal barrel of oil comes from an offshore oil field, its production requires no freshwater, while a marginal barrel extracted at an onshore field using CO_2 injection can be very water-intensive. For irrigated biofuel feedstocks such as corn grain, the location in which the marginal unit of grain production occurs determines the amount of irrigation water required. For electricity, the location and electricity mix in that region determine the water intensity.

In order to capture the impact of such variances on the final results, three scenarios are presented: low, average, and high water use, with the understanding that the marginal unit could resemble any of the scenarios, or something in between. These scenarios are developed by varying key inputs, as listed in the SI, Table S12. The results of this sensitivity analysis are shown in Figure 2c. Changes in irrigation inputs produce some of the most striking differences.

For example, by irrigating Miscanthus (shown in the "high" case) and removing the electricity co-production credit, the Miscanthus total water footprint is higher than that of the "average" corn grain/stover case. Although not captured here, the water impacts of irrigation may be somewhat countered by resulting increases in yield; for example, reference (*40*) points out that irrigating Miscanthus increases biomass yield, particularly when paired with an increase in nitrogenous fertilizer application.




L Water / km Traveled
20
15
10
5
0
-5
-10
C
W
C
W
C
W
C
W
C
W
C
W
Crude Oil to Gasoline
Oil Sands to Gasoline
Miscanthus to Ethanol
Avg Corn Grain & Stover to Ethanol
Rainfed Corn Grain & Stover to Ethanol
Electricity: U.S. Mix
Electricity Consumption
Supply-Chain Services
Supply-Chain Agriculture
Construction & Materials
Chemicals
Primary Fuel Consumption
Direct

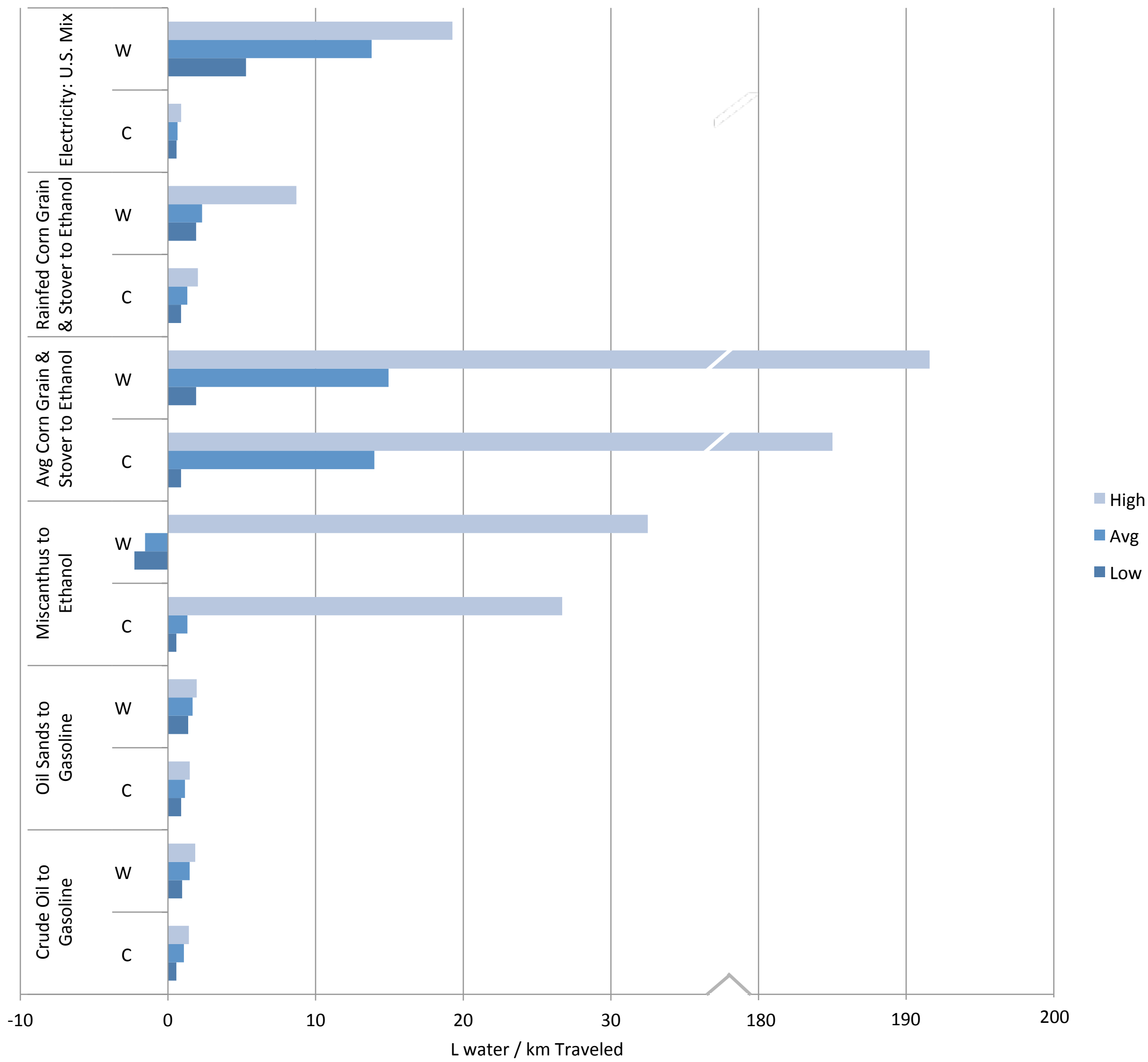


Figure 2a: Water Use Broken Down by Life-Cycle Phase

Figure 2b: Water Use Broken Down by Major Contributor

Figure 2c: High, Average, and Low Water Use Scenarios Broken Down by Major Contributing Factors

Water Use Weighted by Potential Stress

In order to derive meaningful conclusions from the LCI results, it is important to make a connection between water use and its ultimate consequences. Using large quantities of water in an area whose water resources vastly exceed local needs is likely less problematic than small quantities in locations where water is severely limited. As discussed previously, the authors take a simpler, more accessible approach to gauging potential impacts. U.S. counties are identified as being vulnerable to surface water shortages (droughts) if they spent greater than 10% of the previous 100 years in severe, extreme, or exceptional drought. States are identified as having vulnerable groundwater if there are records of water table drop, subsidence, or other overpumping impacts in the recent past, although it should be mentioned that groundwater levels are dependent on numerous factors and may increase some years and decrease in others. The states identified here display long-term downward trends. Figures 3a and 3b show the results for surface water and groundwater consumption, respectively, and the fraction of which occurs in potentially vulnerable areas. The first takeaway message from these graphs is that biofuels may place a larger burden on groundwater than electricity or gasoline production in some circumstances, whereas electricity and gasoline depend more heavily on surface water. The resulting burden from biofuels production is highly dependent on whether the crop requires irrigation. Secondly, the fraction of water consumption that occurs in vulnerable areas varies widely between fuels, as well as between groundwater and surface water. For example, Florida is not considered to be as drought-prone as many areas in the United States, so surface water use for power generation in the Florida Reliability Coordinating Council (FRCC) region may not be as problematic as in other regions. However, Florida does experience negative impacts resulting from groundwater pumping, so any groundwater used for FRCC power generation is likely to have more negative impacts than in other NERC regions. In contrast, Midwest Reliability Organization (MRO) and Hawaiian Islands Coordinating Council (HICC) electricity place an unusually high burden on drought-prone areas.

Another impact of water use is an increase in GHG emissions that results from energy use for pumping and treating water for irrigation, cooling, mining/extraction, and industrial use. In this research, all activities required to supply freshwater to a variety of users are considered, including groundwater pumping, surface water pumping, as well as treatment and distribution. Based on a national average GHG-per-liter characterization factor, the GHG footprint of water does not contribute significantly to the life-cycle footprint of transportation fuels (see SI Section 4). However, in locations where water is scarce and must be imported, desalinated, or recycled (for example, parts of CA, FL, and TX) the GHG footprint of water is much larger. These more GHG-intensive water supplies serve a variety of users: in California, 18% of total desalination capacity provides freshwater for power plants with closed-loop cooling systems, 23% serves industrial facilities, 1% goes to crop irrigation, and 57% goes to municipal customers (*41*). Because very little irrigation water comes from alternative sources, it is assumed here that only industrial and cooling water may be supplied by these sources. Seven scenarios are explored in which water for industrial and power plant cooling is supplied through alternative means. Irrigation water is not included because the only irrigated crop in this study, corn for grain, is grown primarily in regions not using alternative water supply methods. The scenarios are:

1. Coal-Fired Power Plant w/ Cooling Tower

    Alternative water supply uses: cooling water

2. Natural Gas-Fired Power Plant w/ Cooling Tower

    Alternative water supply uses: cooling water

3. Miscanthus to Ethanol

    Alternative water supply uses: all biorefinery water needs

4. Average Corn Grain & Stover-to-Ethanol

Alternative water supply uses: all biorefinery water needs

5. Rainfed Corn Grain & Stover-to-Ethanol

Alternative water supply uses: all biorefinery water needs

6. Oil Sands to Gasoline

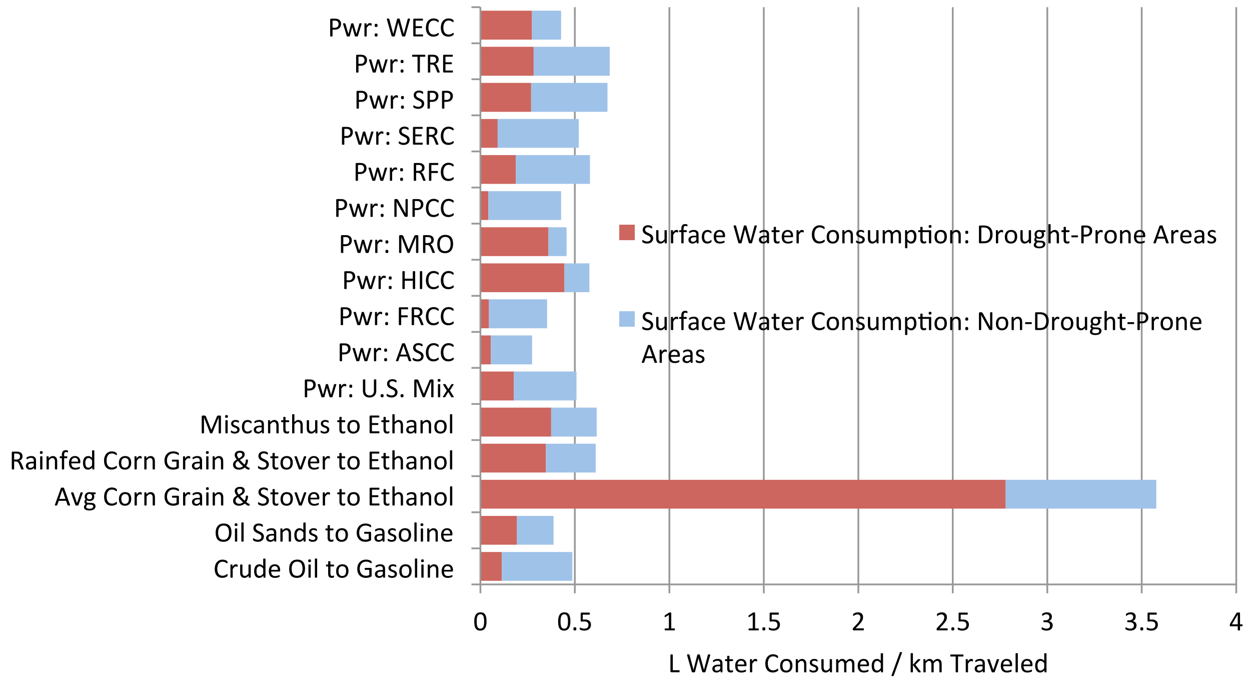
Alternative water supply uses: all petroleum refinery water needs

7. Crude Oil to Gasoline

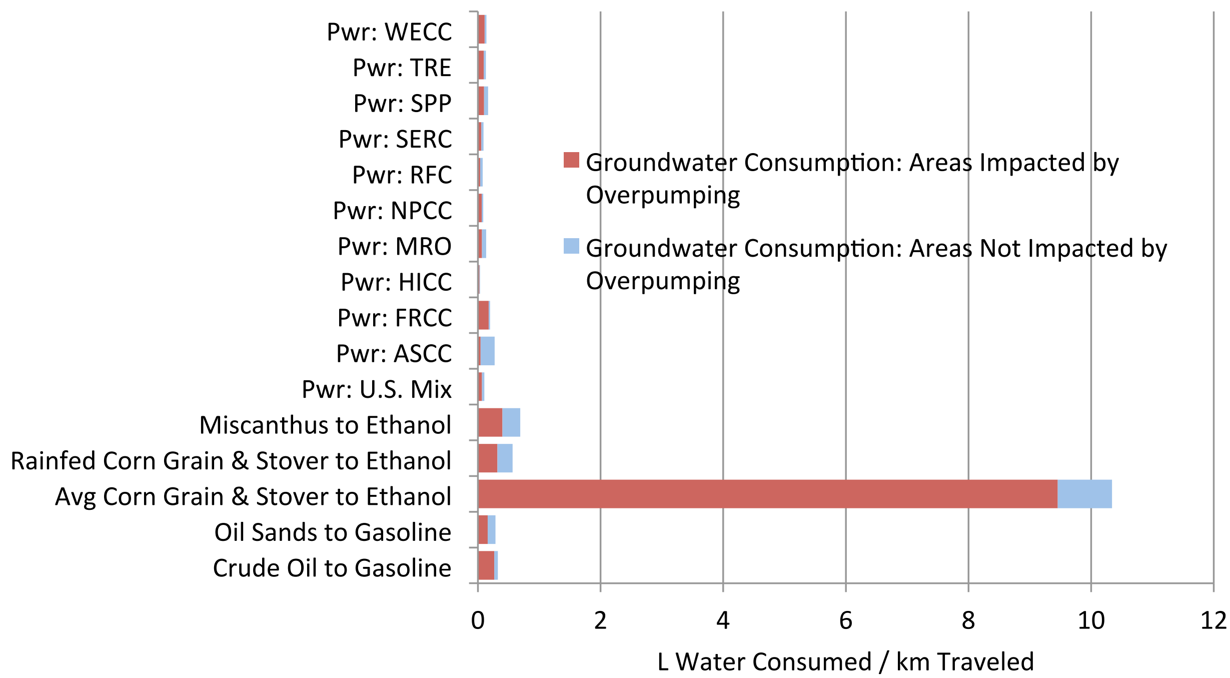
Alternative water supply uses: all petroleum refinery water needs

Figure 3c shows the range of potential changes in total life-cycle GHG footprint of each fuel resulting from the use of imported water (using Southern California imported water as an upper bound), recycled wastewater, desalinated brackish groundwater, and desalinated seawater. Southern California imported water is used because it represents the most energy and GHG-intensive importation in the United States, and thus serves as a maximum. There are, however, less GHG-intensive importation systems such as the gravity-fed delivery of water to New York from the Catskills. This implies that the GHG contribution from alternative water supply systems can range from essentially zero to the upper bounds shown in Figure 3c. The GHG emissions associated with these alternative sources are calculated using the results from (*1*). The full results of this analysis are shown in the SI, Table S21.

As shown in Figure 3c, the GHG footprint of water-use shows the most significant difference for cellulosic ethanol. The footprint of Miscanthus to ethanol can change dramatically, with a minimum increase of 7% and maximum of 47% increase. This additional climate impact associated with water supply should be seriously considered before siting biorefineries in areas that require desalination, wastewater recycling, or importation.


Pwr: WECC
Pwr: TRE
Pwr: SPP
Pwr: SERC
Pwr: RFC
Pwr: NPCC
Pwr: MRO
Pwr: HICC
Pwr: FRCC
Pwr: ASCC
Pwr: U.S. Mix
Miscanthus to Ethanol
Rainfed Corn Grain & Stover to Ethanol
Avg Corn Grain & Stover to Ethanol
Oil Sands to Gasoline
Crude Oil to Gasoline
Surface Water Consumption: Drought-Prone Areas
Surface Water Consumption: Non-Drought-Prone Areas
0
0.5
1
1.5
2
2.5
3
3.5
4
L Water Consumed / km Traveled

1


Pwr: WECC
Pwr: TRE
Pwr: SPP
Pwr: SERC
Pwr: RFC
Pwr: NPCC
Pwr: MRO
Pwr: HICC
Pwr: FRCC
Pwr: ASCC
Pwr: U.S. Mix
Miscanthus to Ethanol
Rainfed Corn Grain & Stover to Ethanol
Avg Corn Grain & Stover to Ethanol
Oil Sands to Gasoline
Crude Oil to Gasoline
Groundwater Consumption: Areas Impacted by Overpumping
Groundwater Consumption: Areas Not Impacted by Overpumping
0
2
4
6
8
10
12
L Water Consumed / km Traveled

2

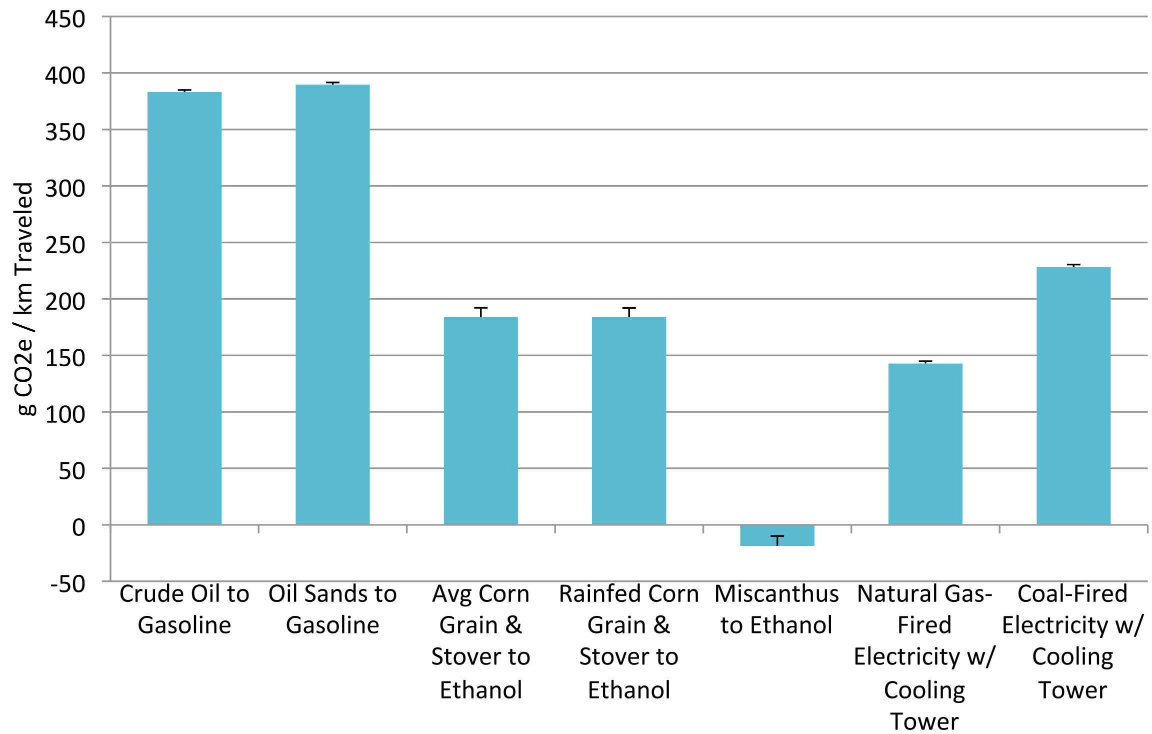


Figure 3a: Surface Water Consumption in Drought and Non-Drought-Prone Areas in the U.S.

Figure 3b: Groundwater Consumption in U.S. Areas Impacted and Not Impacted by Overpumping

Figure 3c: Contribution of Water-Related Greenhouse Gas Emission to the Total Fuel GHG Footprints

Discussion

While the most effective methods for regulating water use over the life cycle of transportation fuels remains undetermined, this paper provides the tools for understanding and reducing the water footprint of transportation fuels, ensuring that, in the effort to protect the climate, water resources are protected as well.

Policy Implications

Historically, water withdrawals and use have been regulated at the local level, where permits for water use by farmers, industrial facilities, etc. can be granted or denied based on local freshwater availability. However, providing nation wide results can guide decision makers in incentivizing certain fuels while avoiding others based on whether particular fuels can be produced using available water resources. The potential water impacts of an aggressive scale-up of alternative transportation fuels through such policies as the CA Air Resources Board's Low Carbon Fuel Standard (LCFS), Energy Policy Act of 2005, and the CA Zero Emission Vehicle (ZEV) Program should be seriously considered.

More generally, there is a need for better monitoring, management, and pricing of water use in the United States. Reference (*42*) points out that U.S. water policy is moving in the right direction, emphasizing full supply cost recovery of future water projects and improving cost recovery for existing projects. Particularly for farmers, the increasing energy costs of pumping groundwater have already incentivized investments in more water-efficient irrigation equipment (*42*). However, reference (*43*) points out that the users rarely pay either the full opportunity cost or the externality costs of their water use.

Ultimately, this paper asserts that as long as policy makers remain cognizant of current and future water resource vulnerability, the alternative transportation fuels examined here have the potential to be produced in such a way that surface and groundwater resources are not threatened. Similarly, these same fuel production pathways also have the potential to exacerbate water stress if the locations of crops, power plants, biorefineries, and other infrastructure are chosen without regard for local short- and long-term water availability.

Limitations of this Analysis

Although this is the most comprehensive LCI of water use for transportation fuel production to date, and the only water LCI that has been weighted by potential impact on water resource stress, there are a number of areas in which improvements can be made. First, this analysis uses a consequential approach where possible, but data availability limits the degree to which this can be done. For example, the origin of the marginal barrel of crude oil consumed in the United States or marginal bushel of corn requires sophisticated economic modeling and hence, the average barrel and average bushel are used. Marginal mixes for electricity use by NERC region should ideally be used as well, whereas average mixes are used here. In contrast, the allocation approach for electricity and ethanol co-produced at biorefineries is decidedly consequential (system expansion inherently measures the net system change).

Another instance in which data availability limits the accuracy of these results is for industries that have yet to develop (specifically, cellulosic ethanol production). The inputs for growing Miscanthus are based on small test plots, and impacts of cellulosic ethanol production come from models of small-scale pilot plants, often using only best practices such as 100% water recycling. As the industry grows and empirical data can be collected, these numbers are likely to change.

Finally, the impact assessment results shown, while informative, may serve as a source of guidance for decision makers, but should not be directly incorporated into policy in their current form. The results serve to demonstrate a simpler method of gauging potential impacts of water use and provide a general sense for which fuels place additional ground and surface water burden in already stressed areas. In the future, researchers should focus on developing better ways of identifying areas whose water resources are vulnerable, particularly with respect to groundwater.

Future Work

This paper presents the most complete water use LCA to date for gasoline, ethanol, and electricity. Because the array of potential transportation energy sources is constantly changing, future studies should include advanced fuels such as butanol, we well as biofuels produced through thermochemical pathways. Diesel and its biofuel substitutes are also poised to gain a larger share of the U.S. market and should also be considered in future studies.

The quality of future LCAs can also be improved through better data availability. Information on water use is often scarce, of questionable quality, or outdated. There are two types of data required for such analyses: water use and water resource. On the usage side, mining/extraction and industrial water requirement information is particularly scarce; the most recent national industrial water use dataset is from 1982 (*44*). Water resource information is also lacking, particularly with respect to groundwater. Reference (*45*) points out that the U.S. Geological Survey has not placed enough emphasis on connecting water use estimates with hydrological data. This paper provides an important first step, but much more can be done to understand how humans impact the hydrologic cycle and what can be done to ensure sustainable freshwater resources for years to come.

Acknowledgements: C. Scown acknowledges the financial support of the National Science Foundation Graduate Research Fellowship. T. McKone acknowledges the financial support of the Energy Biosciences Institute at UC Berkeley. A. Horvath's and C. Scown's contributions to this material are based upon work supported by the California Energy Commission under contract no. MR-06-08.

Legal Notice

Parts of this report were prepared as a result of A. Horvath's and C. Scown's work sponsored by the California Energy Commission (Energy Commission) and the University of California (UC). It does not necessarily represent the views of the Energy Commission, UC, their employees, or the State of California. The Energy Commission, the State of California, its employees, and UC make no warranty, express or implied, and assume no legal responsibility for the information in this report; nor does any party represent that the use of this information will no infringe upon privately owned rights. This report has not been approved or disapproved by the Energy Commission or UC, nor has the Energy Commission or UC passed upon the accuracy of the information in this report.

Supporting Information: A detailed description of data sources, analytical methods, and tables with numerical results are included. The Supporting Information is available free of charge at http://pubs.acs.org, with additional spreadsheets and documentation available for download at www.energy-water-footprint.com.

References

(1) Stokes, J. R.; Horvath, A. Energy and Air Emission Effects of Water Supply. *Environ. Sci. Technol.* **2009,** *43* (8), 2680-2687.

(2) *Water and Sustainability: U.S. Water Consumption for Power Production - The Next Half Century*. 1006786; Electric Power Research Institute: Palo Alto, CA, 2002; http://mydocs.epri.com/docs/public/000000000001006786.pdf

(3) Fthenakis, V.; Kim, H. C. Life-Cycle Uses of Water in U.S. Electricity Generation. *Renewable Sustainable Energy Rev.* **2010,** *14* (7), 2039–2048.

(4) *Water Use for Injection Purposes in Alberta (2006 Update)*. Geowa Information Technologies, Ltd.: Calgary, Alberta, Canada, 2006; http://www.waterforlife.gov.ab.ca/docs/Water_Use_Injection_Purposes_2006_Update.pdf

(5) *Energy Demands on Water Resources: Report to Congress on the Interdependency of Energy and Water*. U.S. Department of Energy: Washington, D.C., 2006; http://www.sandia.gov/energy-water/docs/121-RptToCongress-EWwEIAcomments-FINAL.pdf

(6) Chiu, Y. W.; Walseth, B.; Suh, S. Water Embodied in Bioethanol in the United States. *Environ. Sci. Technol.* **2009,** *43* (8), 2688-2692.

(7) Gleick, P. H. Water and Energy. *Annu. Rev. Energy Environ.* **1994,** *19* (1), 267-299.

(8) King, C. W.; Webber, M. E. Water Intensity of Transportation. *Environ. Sci. Technol.* **2008,** *42* (21), 7866-7872.

(9) Torcellini, P.; Long, N.; Judkoff, R. *Consumptive Water Use for U.S. Power Production*. NREL/TP-550-33905; National Renewable Energy Laboratory: Golden, CO, 2003; http://www.nrel.gov/docs/fy04osti/33905.pdf

(10) Wu, M.; Mintz, M.; Wang, M.; Arora, S. *Consumptive Water Use in the Production of Bioethanol and Petroleum Gasoline*. Argonne National Laboratory: Argonne, IL, 2009; http://www.transportation.anl.gov/pdfs/AF/557.pdf

(11) *Water and Sustainability: U.S. Electricity Consumption for Water Supply & Treatment - The Next Half Century*. 1006787; Electric Power Research Institute: Palo Alto, CA, 2002;

http://www.rivernetwork.org/sites/default/files/Water%20and%20Sustainability%20(Volume%204)-%20EPRI.pdf

(12) *California Agricultural Water Electrical Energy Requirements*. R 03-006; California Energy Commission: Sacramento, CA, 2003; http://www.itrc.org/reports/energyreq/energyreq.pdf

(13) Stokes, J.; Horvath, A. Life Cycle Energy Assessment of Alternative Water Supply Systems. *Int. J. Life Cycle Assess*. **2005,** *11* (5), 335-343.

(14) 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*. U.S. Geological Survey: Washington, D.C., 2009; http://pubs.usgs.gov/circ/1344/pdf/c1344.pdf

(15) Davis, S. C.; Diegel, S. W.; Boundy, R. G. *Transportation Energy Data Book - Edition 27*. Oak Ridge National Laboratory: Oak Ridge, TN, 2008; http://www-cta.ornl.gov/data/tedb27/Edition27_Full_Doc.pdf

(16) de Fraiture, C.; Giordano, M.; Liao, Y. Biofuels and Implications for Agricultural Water Use: Blue Impacts of Green Energy. *Water Policy* **2008,** *10* (Supplement 1), 67-81.

(17) Fingerman, K. R.; Torn, M. S.; O'Hare, M. H.; Kammen, D. M. Accounting for the Water Impacts of Ethanol Production. *Environ. Res. Lett*. **2010,** *5*.

(18) Gerbens-Leenes, W.; Hoekstra, A. Y.; Meer, T. H. v. d. The Water Footprint of Bioenergy. *Proc. Natl. Acad. Sci. U. S. A.* **2009,** *106* (25).

(19) Harto, C.; Meyers, R.; Williams, E. Life Cycle Water Use of Low-Carbon Transport Fuels. *Energy Policy* **2010,** *38* (9), 4933-4944.

(20) Schnoor, J. L.; Doering Iii, O. C.; Entekhabi, D.; Hiler, E. A.; Hullar, T. L.; Tilman, G. D.; Logan, W. S.; Huddleston, N.; Stoever, M. J. *Water Implications of Biofuels Production in the United States*. National Research Council: Washington, D.C., 2008; http://books.nap.edu/openbook.php?record_id=12039

(21) Chapagain, A. K.; Hoekstra, A. Y. *Water Footprints of Nations*. UNESCO-IHE: Delft, The Netherlands, 2004; http://www.waterfootprint.org/Reports/Report16Vol1.pdf

(22) *Annual Energy Review 2007*. U.S. Energy Information Administration: Washington, D.C., 2007; http://www.eia.doe.gov/aer/

(23) Reisner, M., *Cadillac Desert: The American West and its Disappearing Water*. Penguin Group: New York, NY, 1993.

(24) Koehler, A. Water Use in LCA: Managing the Planet's Freshwater Resources. *Int. J. Life Cycle Assess.* **2008,** *13* (6), 451-455.

(25) Bovolo, C. I.; Parkin, G.; Sophocleous, M. Groundwater Resources Climate and Vulnerability. *Environ. Res. Lett.* **2009,** *4*.

(26) Shah, T. Climate Change and Groundwater: India's Opportunities for Mitigation and Adaptation. *Environ. Res. Lett.* **2009,** *4* (3), 1-13.

(27) Bartolino, J. R.; Cunningham, W. L. *Ground-Water Depletion Across the Nation.* FS-103-03; U.S. Geological Survey: Reston, VA, 2003; http://pubs.usgs.gov/fs/fs-103-03/JBartolinoFS%282.13.04%29.pdf

(28) Graedel, T. E.; Allenby, B. R., *Industrial Ecology*. Prentice Hall: Upper Saddle River, NJ, 2003.

(29) Hendrickson, C.; Horvath, A.; Joshi, S.; Lave, L. Economic Input-Output Models for Environmental Life-Cycle Assessment. *Environ. Sci. Technol.* **1998,** *32* (7), 184A-191A.

(30) *Economic Input-Output Life Cycle Assessment (EIO-LCA) US 2002 (428) model.* Carnegie Mellon University Green Design Institute: Pittsburgh, PA, 2010; http://www.eiolca.net/

(31) Blackhurst, M.; Hendrickson, C.; Vidal, J. S. i. Direct and Indirect Water Withdrawals for U.S. Industrial Sectors. *Environ. Sci. Technol.* **2010,** *44* (6), 2126-2130.

(32) Pfister, S.; Koehler, A.; Hellweg, S. Assessing the Environmental Impacts of Freshwater Consumption in LCA. *Environ. Sci. Technol.* **2009,** *43* (11), 4098-4104.

(33) King, C. W.; Webber, M. E. The Water Intensity of the Plugged-In Automotive Economy. *Environ. Sci. Technol.* **2008,** *42* (12), 4305-4311.

(34) *The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model*, 1.8c; Argonne, IL, 2009; http://www.transportation.anl.gov/modeling_simulation/GREET/

(35) Bates, B.; Kundzewicz, Z. W.; Wu, S.; Palutikof, J. *Climate Change and Water*. IPCC Technical Paper VI; Intergovernmental Panel on Climate Change: Geneva, Switzerland, 2008; http://www.ipcc.ch/pdf/technical-papers/climate-change-water-en.pdf

(36) U.S. Drought Monitor: Historical Maps of the Palmer Drought Index. http://www.drought.unl.edu/whatis/palmer/pdsihist.htm (6/10/10),

(37) Hayes, M. J. *What is Drought? Drought Indices*. National Drought Mitigation Center: Lincoln, NE, 2006; http://www.drought.unl.edu/whatis/indices.htm

(38) Galloway, D. L.; Jones, D. R.; Ingebritsen, S. E. *Ground-Water Resources for the Future: Land Subsidence in the United States*. FS-165-00; U.S. Geological Survey: Reston, VA, 2000; http://water.usgs.gov/ogw/pubs/fs00165/SubsidenceFS.v7.PDF

(39) Peck, J. C., Groundwater Management in the High Plains Aquifer in the USA: Legal Problems and Innovations. In *Groundwater Revolution: Opportunities and Threats to Development*, Giordano, M.; Villholth, K. G., Eds. CAB International: Colombo, Sri Lanka, 2007; pp 296-319.

(40) Ercoli, L.; Mariotti, M.; Masoni, A.; Bonari, E. Effect of Irrigation and Nitrogen Fertilization on Biomass Yield and Efficiency of Energy Use in Crop Production of *Miscanthus*. *Field Crops Research* **1999,** *63* (1), 3-11.

(41) Cooley, H.; Gleick, P. H.; Wolff, G. *Desalination, With a Grain of Salt*. Pacific Institute: Oakland, CA, 2006; http://www.pacinst.org/reports/desalination/desalination_report.pdf

(42) Wichelns, D. *Agricultural Water Pricing: United States*. Organisation for Economic Co-Operation and Development: Paris, France, 2010; http://www.oecd.org/dataoecd/26/22/45016437.pdf

(43) Rogers, P.; Silva, R. d.; Bhatia, R. Water is an Economic Good: How to Use Prices to Promote Equity, Efficiency, and Sustainability. *Water Policy* **2002,** *4* (1), 1-17.

(44) *Water Use in Manufacturing*. MC82-S-6; U.S. Census Bureau: Washington, D.C., 1984;

(45) Maidment, D. R.; Bradbury, K. R.; Bradley, A. A.; Baker, V. R.; Barros, A. P.; Campana, M. E.; Dziegielewski, B.; Poff, N. L.; Prestegaard, K. L.; Schwartz, S. S.; Siegel, D. I.; Snoeyink, V. L.; Stoertz, M. W.; Thompson, K. D., *Estimating Water Use in the United States: A New Paradigm for the National Water-Use Information Program*. National Academy Press: Washington, DC, 2002.