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# Water Embodied in Bioethanol in the United States

YI-WEN CHIU,[1] BRIAN WAL SETH,* * * AND SANGWON SUH**

Water Resources Science and Department of Bioproducts and Biosystems Engineering, University of Minnesota, 1390 Eckles Avenue, St. Paul, Minnesota 55108

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Prior studies have estimated that a liter of bioethanol requires 263-784 L of water from corn farm to fuel pump, but these estimates have failed to account for the widely varied regional irrigation practices. By using regional time-series agricultural and ethanol production data in the U.S., this paper estimates the state-level field-to-pump water requirement of bioethanol across the nation. The results indicate that bioethanol's water requirements can range from 5 to 2138 L per liter of ethanol depending on regional irrigation practices. The results also show that as the ethanol industry expands to areas that apply more irrigated water than others, consumptive water appropriation by bioethanol in the U.S. has increased 246% from 1.9 to 6.1 trillion liters between 2005 and 2008, whereas U.S. bioethanol production has increased only 133% from 15 to 34 billion liters during the same period. The results highlight the need to take regional specifics into account when implementing biofuel mandates.

## 1. Introduction

The annual bioethanol production capacity in the United States has reached 34 billion liters as of July 2008 (1, 2), exceeding the 2008 biofuel production mandate of 32 billion liters under the Energy Independence and Security Act (EISA) (3). Under the EISA, conventional biofuel production will need to further increase to 57 billion liters by 2015 (4). Currently, more than 95% of U.S. bioethanol is produced using corn for grain (5).

Although bioethanol's climate change benefits (6-8), ecological impacts (9), energy efficiency, and impacts on environmental quality (10-12) have been the main focus of recent studies, corn ethanol's implications on water environment have also raised significant concerns among the research community (13-17). The National Research Council, for instance, warned that corn ethanol production increases may significantly impact water quality and availability (14).

Highlighting ethanol's dependence on water, prior studies estimated the total field-to-pump water use by 1L of ethanol to be between 263 and 784 L (Table 1) (15,18-20). However, these estimates have failed to account for the widely varied regional water use practices.

This study estimates the corn farm to fuel pump water requirement per liter of ethanol, which is termed here embodied water in ethanol (EWe) (see the Supporting Information), in 41 corn producing states from 2005 to 2008 using the most detailed regional and state statistics. EWe is defined here as the sum of irrigated water ($W_{IR}$) at corn farms for feedstock production as well as the process water ($W_P$) consumed within biorefineries, divided by total ethanol production within a state, which is presented in liters of water per liter of ethanol ($L\ L^{-1}$). Naturally occurring, direct precipitation to corn fields is not included in WIR to isolate purely anthropogenic water consumption induced by corn ethanol production. Each state's total consumptive water use (TCW) is defined as the sum of $W_P$ and $W_{IR}$ of the state attributable to its bioethanol production.

Given the variability in rainfall, temperature, and climate within the U.S., state irrigation practices differ greatly. We estimated $W_{IR}$ using irrigation data from the U.S. Department of Agriculture (USDA) and U.S. Geological Survey (USGS) (21-23). For corn used by biorefineries, we assumed that corn ethanol was produced using locally grown corn as the primary feedstock, because more than 80% of the corn supply was transported from within 64 km of ethanol facilities *(24)* because of the proximity of ethanol facility location and corn production (Figure 1). Among the 41 corn-producing states, only New Mexico had to import corn from outside the state to fulfill its ethanol production capacity in 2007 (see Table S1 in the Supporting Information).

In addition, only dry-mill facilities were considered in the study because they represent the primary type of facility design. According to the U.S. Environmental Protection Agency (EPA), 206 dry-milling facilities were under operation or construction in 2008, constituting 99% of U.S. ethanol production (5). Water demand by dry-milling processes in the slurring, boiling, fermentation, and distillation stages was taken into account within our calculation. Ground and surface water was also distinguished on the basis the USGS irrigation report (23).

## 2. Materials and Methods

**2.1. Irrigation Rate and Volume.** The volume of irrigated ground and surface water was applied in accordance with the measured irrigation application acres for each state, as reported in the 1997 and 2002 Census of Agriculture (COA), which is conducted within every farm in the U.S. every five years and is made available from U.S. Department of Agriculture's (USDA) National Agricultural Statistics Service (NASS). The more detailed 1998 and 2003 Farm and Ranch Irrigation Survey (FRIS), which reports irrigation depth by crop type by state, is used to calculate irrigation volume for 1997 and 2002. Each FRIS is based on a size-weighted survey of 7% of each state's irrigating farms as reported in the previous year's COA. These reports were used to determine irrigation depth and continuity in irrigated acreages for each state (see Table S1 in the Supporting Information). Climate conditions of corn-producing states that may affect irrigation depth between 1997 and 2002 are analyzed using evapotranspiration models *(25-27),* and no significant difference in climate conditions were found (see the Supporting Information). The COA and FRIS data confirmed that irrigation depth for corn in the U.S. has been relatively stable between surveys. There are several commercially grown corn cultivar varieties designed for short harvest or early maturation in the U.S. A recent study on irrigated corn grown in High Plains reported that water use efficiency between full and short-season corn grain cultivars are the same (28). All the irrigation water was considered as consumptive water. Although some studies define consumptive water as which

TABLE 1. Comparison of Bioethanol's Water Requirements by Previous Studies Expressed in Liters of Water Required to Produce 1 L of Ethanol

| source | process water | irrigation water | total |
|---|---|---|---|
| **Pimentel, 2003 (19)** | **15**[a] | **248** | **263** |
| **Pimentel et al., 2005 (20)** | ***40***[b] | **248** | **288** |
| **de Fraiture et al., 2008 (18)** | **NA** | **400** | **400** |
| **National Research Council, 2008 (15)** | 3.3-4[c] | **780** | **783.3-784** |

[a] Total water required for the process of fermentation and distillation. [b] Detailed unit processes not specified. [c] Indicated net consumption citing various references.

is extracted from and returned to the original watershed (*29*), the definition cannot distinguish the schemes of groundwater usage due to the difference of watershed and aquifer boundaries. Therefore, we classified all the irrigated water as consumptive water in our study.

Furthermore, we determined the portion of ground and surface water irrigation using data published by the U.S. Geological Survey's (USGS) survey of agriculture *(23).* Our study's national results include the 2005, 2006, and 2007 harvest years, and include proportional irrigation information estimated from the latest available USDA national data sets from the 2002 COA as well as the 2003 Irrigation Survey published by the NASS.

**2.2. State Corn Production and Ethanol Requirements.**

For each of the 41 states growing corn, corn production was measured using county-level NASS reports (22) for 2005, 2006, and 2007. In this manner, more than 99% of the nationally reported corn production could be compiled. After determining each county's corn production levels, we measured what portion of each state's production was required for bioethanol production. As illustrated in Figure 1, county corn production closely relates to ethanol facility location. In an earlier study in 2003, Shapouri et al. *(24)* found a similarly close correlation of facility location and corn production in their energy balance study of corn ethanol in the U.S.

**2.3. Facility Operations and Fractionation Process.** The baseline year for ethanol production was established in 2005, as ethanol production increases were proportionally too small to accurately portray the EWe before that time. Single states increasing ethanol production and start-up facility operations had disproportionally magnified effects when compared to the overall corn grain ethanol industry in the U.S. After 2005, existing production volumes were high enough to scale volume in proportion to new production. Each year's capacity, locations, and facility size (nameplate capacity) was derived from data published by the Renewable Fuels Association and the state of Nebraska *(1, 30).*

In addition to the baseline year, ethanol production capacity was modeled for 2006, 2007 and 2008. As new capacity came online each year, it was modeled according to geographic location as well as the production volume of new facilities. Because annual capacity changes nearly every month, we used June as our baseline month for each year's total production volume on a state-by-state basis. For 2008, we modeled both current capacity as of June, as well as production capacity under construction. By assuming that corn for ethanol facilities are sourced within the state considering economic feasibility of long-distance corn transportation (31), a state imports corn only when local supplies are less than the corn demand by in-state ethanol facilities. For these states, we used the national average water demand by corn for the imported portion of corn, because data on its origin is lacking. Overall, the amount of imported corn from other states for ethanol production is negligible.

Within the facility and the fractionation process that occurs there, $W_P$ was calculated from the water demand required for corn slurring, boiling, fermentation, distillation, as well as the system reject water and water released from the evaporators outside the system. As the final step, the ethanol industry blends 5% denaturant to ethanol so that it may not be ingested. Using our survey results we estimated water consumption by dry-mills taking the best-available current technology for water conservation as well as the average corn-to-ethanol yield into account.

## 3. Results

**3.1. Embodied Water in Ethanol by State.** The results show that there is a wide variation in EWe between states ranging from 5 to 2138 L $L^{-1}$. As a general trend, the EWe increases from the East to the West and from the Midwest to the Southwest regions of the U.S. (Figure 2). Among the 19 ethanol-producing states in 2007, Ohio shows the lowest Ewe of 5 L $L^{-1}$, whereas California has the highest EWe of 2138 (Table 2 and Table S2 in the Supporting Information).

The ethanol industry consumed 13 and 17% of U.S. corn production in 2005 and 2007. Incorporating USDA data (22), 28% of the total U.S. corn harvest was estimated to produce 34 billion liters of ethanol in 2008. Of the 15 billion liters of ethanol produced in 2005, 4 billion liters (28%) had a EWe greater than 100 L $L^{-1}$. Of the 17 billion liters of production added from 2006 to 2008,8 billion liters of ethanol production (43%) will have a EWe greater than 100 L $L^{-1}$. The results indicate that EWe and TCW increased by 46 and 68% from 2005 to 2008, respectively. The difference between these two categories illustrates more corn production for ethanol is taking place within highly irrigated regions.

According to our calculation using state-level water use data, the national ethanol-production-weighted average EWe in the U.S. was 142 L $L^{-1}$ in 2007, which is much lower than what was previously estimated in other studies (Table 1). However, the spectrum of EWe is wide enough that the national average is not useful in representing ethanol's water dependence in the U.S. Each state illustrates a significantly different degree of water dependence year by year. Depending on where and how corn was produced, TCW can vary greatly. As Figure 1 illustrates, nationally averaged irrigated water figures are irrelevant in understanding ethanol's water implications, and the discussion should account for regional variations interpreted on a local basis.

**3.2 Local Impacts.** Our results also show that a considerable volume of groundwater was withdrawn for bioethanol in the regions with vulnerable fossil aquifers. For example, the TCWs of South Dakota, Nebraska, Wyoming, Colorado, Kansas, Oklahoma, New Mexico, and Texas, which covers the Ogallala aquifer, amounted to 2.4 trillion liters in 2007, of which 68% was supplied from groundwater. In 2008 these states' TCW will amount to 4.5 trillion liters, which is about 18% of the estimated annual depletion rate of the entire Ogallala aquifer in 2000 *(32-34).* The result indicates that continued expansion of corn production for ethanol in these states may have significant impact on the nation's largest fossil water reservoir.

**3.3 Water Conservation Measures for Bioethanol.** While current water conservation measures for bioethanol have largely focused on biorefineries' process water use *(35),* our results indicate that water conservation can be more effectively achieved by focusing on irrigation reduction. In the short term, future biorefinery sites should be selected such that expansion of corn production for ethanol is not made in the areas that rely on extensive irrigation. In comparison, if the lowest three EWe states increase ethanol production to meet the remaining EISA mandate, the TCW increase will be 61 billion liters, whereas 2.4 trillion liters of water is

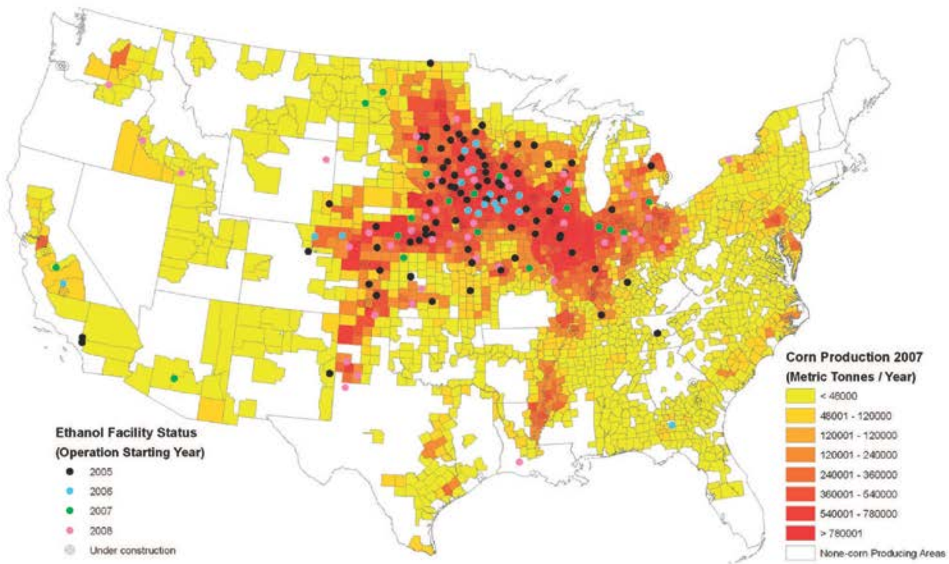


FIGURE 1. County-level corn production and ethanol facilities operating status by 2007. The graph illustrates the proximity of ethanol facilities to corn production.

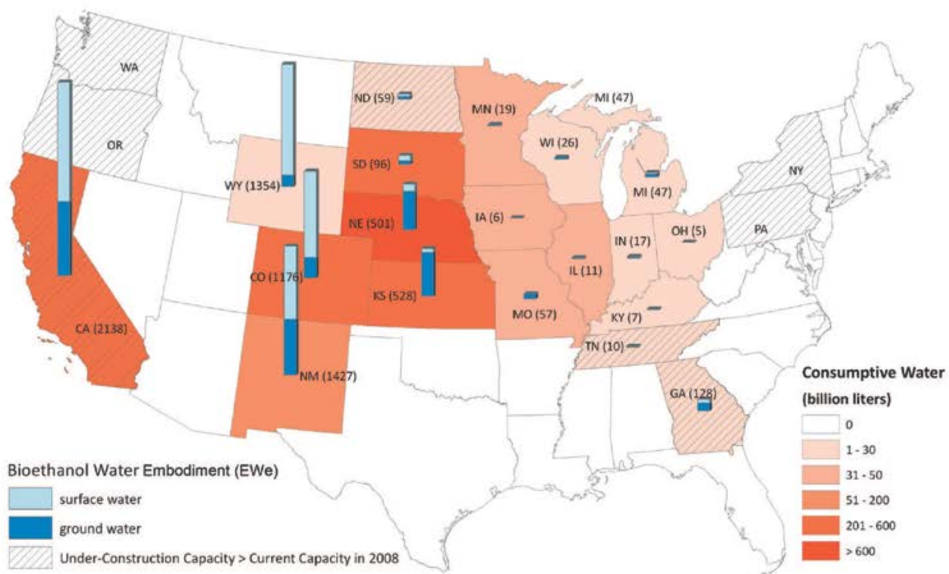


FIGURE 2. EWe and TCW of each state as of 2007. The foreground bar height indicates the EWe of each state, with the portion of ground and surface water indicated by color. The TCW, as measured by a state's EWe and ethanol production (seen in the background), illustrates local and regional ethanol-induced impacts. As is illustrated in Wyoming, a high EWe does not necessarily result in high TCW.

required if the highest seven EWe states increase ethanol production to meet the remaining capacity.

Strategic water pricing may help discourage building new ethanol plants in regions that require large quantities of irrigated water. Using Minnesota as an example, the average price of water for industrial use from public supply systems is 54 cents per cubic meter in 2008, according to our survey (36). The price of irrigated water or permitted water withdrawal can be as low as 2.1 to 3.7 cents per cubic meter (37). Average water price in the U.S. is the lowest (66 cents per cubic meter) among industrialized countries according to a survey result (38). Water price has significant implications not only to site selection of new ethanol facilities but also to voluntary water conservation efforts by large quantity water-users (39).

TABLE 2. EWe and TCW in the 19 ethanol-producing states in 2007 ranked according to each state's EWe. All numbers are listed in million liters, unless otherwise specified, and the figures may not sum to totals because of independent rounding

| state | ethanol production | EWe ($L\ L^{-1}$) | EWe ($L\ L^{-1}$) | | Wr | Wp | TCW | corn processed into ethanol |
|---|---|---|---|---|---|---|---|---|
| | | | ground water | surface water | | | | |
| Ohio | 11 | 5 | 4 | 1 | 11 | 41 | 52 | 0.20% |
| Iowa | 6857 | 6 | 6 | 0 | 17288 | 24 745 | 42 032 | 28% |
| Kentucky | 134 | 7 | 4 | 4 | 472 | 484 | 956 | 7% |
| Tennessee | 254 | 10 | 6 | 5 | 1681 | 915 | 2597 | 29% |
| Illinois | 3486 | 11 | 11 | 0 | 27 389 | 12 581 | 39 970 | 15% |
| Indiana | 954 | 17 | 11 | 6 | 12 539 | 3442 | 15 981 | 9% |
| Minnesota | 2296 | 19 | 16 | 3 | 34 589 | 8286 | 42 875 | 19% |
| Wisconsin | 1067 | 26 | 26 | 0 | 24 208 | 3852 | 28 060 | 23% |
| Michigan | 587 | 47 | 31 | 16 | 25 177 | 2117 | 27 295 | 19% |
| Missouri | 587 | 57 | 55 | 2 | 31 156 | 2117 | 33 273 | 12% |
| North Dakota | 505 | 59 | 31 | 28 | 28 146 | 1824 | 29 970 | 18% |
| South Dakota | 2203 | 96 | 38 | 58 | 203 762 | 7950 | 21712 | 39% |
| Georgia | 2 | 128 | 85 | 42 | 188 | 5 | 194 | 0.25% |
| Nebraska | 2481 | 501 | 422 | 80 | 1 235 128 | 8954 | 1 244 082 | 16% |
| Kansas | 804 | 528 | 486 | 42 | 421 840 | 2903 | 424 743 | 15% |
| Colorado | 322 | 1176 | 226 | 950 | 377 082 | 1161 | 378 243 | 20% |
| Wyoming | 19 | 1354 | 125 | 1229 | 25 547 | 68 | 25 615 | 23% |
| New Mexico | 114 | 1427 | 615 | 812 | 161 587 | 410 | 161 997 | 113% |
| California | 257 | 2138 | 814 | 1323 | 549 240 | 929 | 550 169 | 68% |
| Average[3] | | 142 | 91 | 51 | | | | 23% |

[3] Average is weighted by ethanol production in 2007 and calculated for the purpose of comparison only. Because of the large variation between regions, significance of the average for representing the nation's EWe is limited.

Although informed biorefinery site selection will be able to reduce the increasing pressure of ethanol industry expansion in the areas that rely more on irrigation, immediate action needs to be taken to materialize any impact by site selection. Existing biorefineries and facilities under construction already account for 51 billion liters of ethanol production capacity, leaving only 6 billion liters of unbuilt production capacity before the EISA's 2015 mandate is met. The remaining 6 billion liters of ethanol production capacity is expected to be exhausted by future development plans over the next two years if current trends continue. Other water conservation strategies including improvement in corn genetics, irrigation practices, and strategic water pricing should also be examined.

## 4. Discussion

The embodied water calculations in this study rely on the water consumption by corn farms estimated from irrigation statistics. Previous studies used evapotranspiration models to estimate water consumption by corn. A recent study (40) estimates the corn water requirement of the U.S. to be 308 L per kg of corn, which can be translated into 725 L L-1 of EWe with a corn-to-ethanol conversion rate of 0.43 L per kg of corn. The Ewe figure calculated from (40) is based on evapotranspiration modeling, and therefore, it includes both irrigation water and natural precipitation, which makes a direct comparison with our results difficult. Another study (41) estimates life-cycle water consumption by different fuel types per mile of light duty vehicle traveled, which translates into 497 L L-1 of average embodied water in irrigated-corn ethanol in the U.S. Our estimates for the temperate-climate states are in good agreement with this result, whereas our results provide finer spatial resolution.

By quantifying field-to-pump water consumption, our results show a clear picture of geographical differences in EWe, which demonstrates why it is critical to clarify regional disparities in understanding bioethanol's water implications. In particular, the results show that: (a) the national average is not relevant in understanding bioethanol's water implications as bioethanol's water consumption ought to take regional irrigation practices into account; (b) as corn ethanol production expands geographically, bioethanol appropriates more irrigated water over time; and (c) the efforts to reduce water consumption by bioethanol needs to take a systems approach.

To reduce the water requirements to meet the 57 billion liter conventional biofuel production mandate by 2015 under the EISA, future expansion of corn ethanol production needs to take regional or county-level water use practices into account. Our study also shows that corn ethanol produced in the High Plains aquifer appropriates large amounts of groundwater from vulnerable fossil resources. Continued expansion of corn ethanol development in those regions will have more significant impacts on water sustainability than that in regions with no or little irrigation.

Our study highlights the need to strategically promote ethanol development in the states with lower irrigation rates and with less fossil groundwater use. According to the survey conducted by the United States General Accounting Office (GAO) in 2003, 36 out of 47 states expect varied degrees of water shortages within the next decade (42). It is notable that all the high-EWe states in our study were those classified in the GAO survey as to be likely to experience statewide (Colorado), regional (Wyoming), local (Kansas and Oklahoma), or uncertain water shortages (California and New Mexico). Continued expansion of corn production in these regions is likely to further aggravate expected water shortages of the region.

The time left for improving water consumption is limited. To achieve substantial EWe reduction, we have to pay attention not only to biorefineries but also to regional irrigation practices. As the 57 billion liters of annual ethanol production mandate is 90% fulfilled by current operating biorefineries and facilities under construction, concerted and immediate action needs to be taken in order to prevent a problem shift from energy supply to water sustainability.

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**Supporting Information Available**

Tables of input data including ethanol production, irrigation, and water sources of each state used to derive water consumption and to calculate embodied water in ethanol; detailed data on embodied water in ethanol from 2005 to 2008 by state and appropriated water sources (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

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