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Life Cycle Water Consumption and Withdrawal Requirements of Ethanol from Corn Grain and Residues

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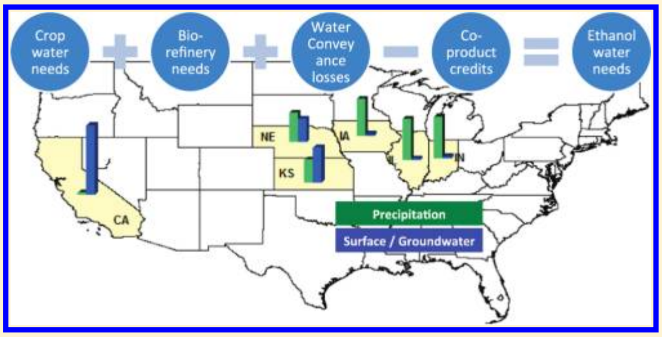
S Supporting Information

ABSTRACT: We assessed the water requirements of ethanol from corn grain and crop residue. Estimates are explicit in terms of sources—green (GW) and blue (BW) water, consumptive and nonconsumptive requirements across the lifecycle, including evapotranspiration, application and conveyance losses, biorefinery uses, and water use of energy inputs, and displaced requirements or credits due to coproducts. Ethanol consumes 50−146 L/vehicle kilometer traveled (VKT) of BW and 1−60 L/VKT of GW for irrigated corn and 0.6 L/VKT of BW and 70−137 L/VKT of GW for rain-fed corn after coproduct credits. Extending the system boundary to consider application and conveyance losses and the water requirements of embodied energy increases the total BW withdrawal from 23% to 38% and BW + GW consumption from 5% to 16%. We estimate that, in 2009, 15−19% of irrigation water is used to produce the corn required for ethanol in Kansas and Nebraska without coproduct credits and 8−10% after credits. Harvesting and converting the cob to ethanol reduces both the BW and GW intensities by 13%. It is worth noting that the use of GW is not without impacts, and the water quantity and water quality impacts at the local/seasonal scale can be significant for both fossil fuel and biofuel.



1. INTRODUCTION

Major biofuel programs supported in the United States and other countries have raised the discussion about sustainability implications of biofuels, including the impact on wildlife, biodiversity, land use, air pollution, and water resources.[1] A few recent studies have estimated the "consumptive water use", "water embodied", and "water footprint" of ethanol from corn grown in the United States.[2−6] As shown in the Supporting Information, part II, Table SII 1.1, estimates of water used by corn ethanol differ by orders of magnitude: ranging from 1.1 to 335 L/vehicle kilometer traveled (VKT) for Iowa and from 59 to 214 L/VKT for Nebraska. The major difference between these studies stems from the debate existing in the water life cycle analysis (LCA) literature regarding whether, and how, to include consumption of green water (GW), which comes from precipitation before and during the crop season and is stored as soil moisture.[7−10]

Pfister et al.[10] argue that impacts of GW consumption should be studied under land use, not water use, impact analysis. Land occupation for cultivation provides access to GW just as it does to solar radiation, wind, and soil. Milà i Canals et al.[9] recommend only estimating changes in blue water (BW) (surface water and groundwater) formation due to land use changes. Conversion of natural vegetation to cultivated land can change interception of GW and affect BW formation in the form of infiltration and runoffs.[9,11]

Studies that estimate GW along with BW use provide a comprehensive assessment of total crop water demand in a given region. Estimation of GW use is important to understand the overall hydrological impacts of bioenergy production[8] and allows a consistent comparison of water use across different biofuel crops.[12] Explicit reporting of GW requirements acknowledges competing demands for limited freshwater.[8] Furthermore, estimates that include total water use are more robust than those focusing on BW use alone. Drought in any single year will necessitate application of more irrigation water to compensate for lower precipitation; although total evapotranspiration remains fairly constant. For example, statewide average irrigation water application for corn cultivation in Nebraska was 24.4 and 27.4 cm in 2008 and 1997, respectively, but 36.6 cm in 2003[13−15] because of drought conditions.[16] An inventory of BW use alone undertaken during a normal year would underestimate BW use in a drought year; only by including the GW use can an accurate estimate be achieved.

To address the controversy regarding GW use, this study explicitly states the sources of water inputs (GW versus BW and surface water versus groundwater). Our water accounting system also considers different types of uses (consumptive, nonconsumptive, and withdrawal) and accounts for application losses, conveyance losses, water use of direct energy inputs throughout

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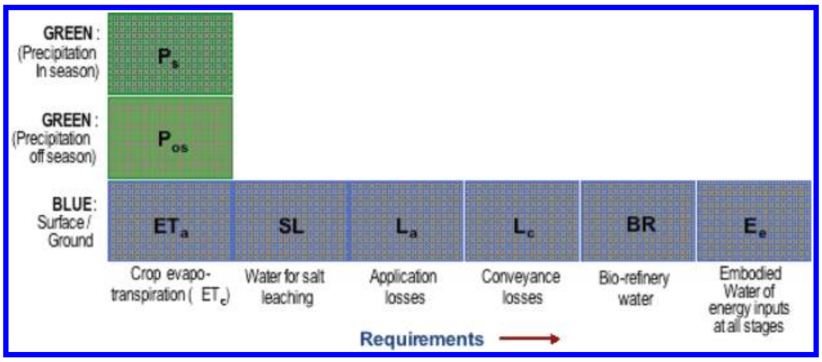

Figure 1. Water withdrawal and consumptive requirements of ethanol from corn grain and crop residue by life cycle stages and by source of water.

Table 1. Life Cycle Consumptive and Nonconsumptive Water Requirements of Ethanol Production

Water Requirement	Consumptive Use or Loss	Nonconsumptive Use or Loss
Cultivation Stage		
crop evapotranspiration (ET_c)	• ET of applied water	
	• Effective precipitation (P_s) and soil moisture depletion (P_{os})	
salt leaching (SL)		• Deep percolation below the root zone
application losses (L_a)	• Evaporation from the soil surface, open ditches, and the crop canopy	• Runoff and seepage losses
	• Drift losses (sprinkler system)	
conveyance losses (L_c)	• Evaporation from open canals	• Seepage losses
	• ET by vegetation in and around canals	
Ethanol Production Stage		
biorefinery (BR)	• Process water	
	• Cooling tower evaporation	
All Stages		
embodied water of energy inputs (E_e)	• Water consumption during production of fuels—diesel, electricity, etc.—used across the life cycle	• Not calculated

the life cycle, and coproduct credits. In section 2, we detail our system boundary and methodology. In section 3, we describe our assumptions and data sources. Results are presented in section 4. We discuss the caveats of our research and areas for future research in section 5.

2. SYSTEM BOUNDARY AND WATER REQUIREMENTS

2.1. Definition of Water Use Indicators. We estimate three types of water use: BW withdrawal, BW consumption, and GW consumption. *Consumptive use* indicates the use of freshwater when release into the current watershed does not occur because of evaporation, evapotranspiration, and product integration, discharge to the sea, or percolation to the salt sink.[7,9,17] *BW withdrawal* is the removal from a surface water body or aquifer. The water withdrawn is used both consumptively and nonconsumptively. BW used *nonconsumptively* is released back to the environment with or without change in quality, through recycling to water bodies, seepage, and runoff, and is available for alternative uses in the same watershed. Unlike BW, GW use is considered only in a consumptive sense. Figure 1 summarizes the various water requirements considered in the study. Table 1 divides the requirements into consumptive and nonconsumptive portions.

Recent studies estimating water requirements of biofuels focus on consumptive use and do not consider withdrawal requirements.[2−6] The distinction between withdrawal and consumption depends upon the spatial boundary selected for analysis. Excess water runoff from an upstream cultivated land arising from irrigation system inefficiencies can be beneficially used downstream. Seepage losses from unlined irrigation canals can recharge aquifers or have other environmental benefits. As an example, estimates of water use efficiencies for individual systems in the Nile Basin in Egypt are around 30%, but the overall efficiency for the entire Nile system is estimated at 80%.[18] The concept is summarized by Perry et al.,[19] who indicate that "...'losses' at the scale of an individual field or an irrigation project are not necessarily 'losses' in the hydrological sense...". Estimation of withdrawal and nonconsumptive use of BW is, however, essential as excess irrigation water leaches salts and implies higher pumping costs. Significant water withdrawals from surface water bodies may exert localized and/or seasonal impacts on the ecosystem. Extraction of groundwater beyond recharge rates could lead to aquifer depletion. As a result, estimation of both withdrawal and consumption intensity conveys important information.

Water usage is estimated in the form of L/VKT and hence is referred to as the water intensity. Use of the terms water "use" and "requirements" is applicable to both withdrawal and consumption.

2.2. Elements of the Life Cycle Considered. The life cycle of biofuels considered in this study includes feedstock cultivation, storage, and transport, ethanol production and distribution, and the direct energy inputs at various stages of the life cycle. Water requirements across the life cycle (Figure 1) extend beyond requirements considered by earlier studies that consider only crop evapotranspiration (ET_c) or irrigation (ET_a) and process and cooling water consumed during ethanol conversion (BR) (the Supporting Information, part II, section 2, compares system boundaries). We also consider application losses due to irrigation system inefficiencies (L_a), water for salt leaching (SL), losses during irrigation water conveyance (L_c), and water requirements of fuels used at the life cycle stages listed above.

ET_c constitutes the greatest proportion of water requirements for bioethanol production and is a function of climatic conditions and crop characteristics. For rain-fed crops, demand for ET_c is met entirely through precipitation before and during the crop season ($P_s + P_{os}$). Irrigation water (ET_a) may be applied in certain regions where GW is insufficient to meet ET_c requirements. The fraction of ET_c met through GW ($P_s + P_{os}$) also depends upon the moisture holding capacity of the soil and the root depth of the crop. P_s captures "effective" precipitation—total precipitation during the crop season minus any runoff or percolation below the root zone.

Prior to planting of corn, preirrigation water (SL) may be applied to flush excess salts through the soil.[20] The volume of SL depends upon precipitation, the amount of salt accumulation (which in turn depends upon the extent and salt content of irrigation water applied), and finally seepage losses from excess water application. For irrigated crops, excess application (L_a) is necessary to account for uniformity, soil evaporative losses, runoff and seepage from water distribution ditches for surface irrigation systems, and wind drift and evaporative losses from the spray and crop canopy for sprinkler systems.[21] Conveyance losses (L_c) result from evaporation and evapotranspiration by vegetation in and near canals, percolation to the salt sink, and seepage through canals that may return as surface flows or recharge groundwater. SL, L_a, and L_c are required only for irrigated corn.

In addition to direct water inputs, we consider upstream water consumed to produce fuels—diesel, electricity, natural gas, and coal—required during corn cultivation, storage, and distribution and ethanol production (E_e).

2.3. Feedstocks and Geographical Regions Considered. We analyze the water requirements of ethanol from the corn grain and the cob (crop residue). We do not consider using the entire stover as feedstock due to the concerns of detrimental impacts on soil fertility[22] and shortcomings in competitive economics in transportation and distribution[23] and harvesting[23] of the feedstock. In this paper we focus on ethanol from corn grown in California (CA) and in the U.S. Corn Belt—specifically Illinois (IL), Indiana (IN), Iowa (IA), Kansas (KS), and Nebraska (NE). These states together accounted for more than 50% of U.S. corn in 2009[24] and are likely to witness significant increases in corn cultivation and ethanol production from both grain and agricultural residue due to aggressive targets set forth in the Renewable Fuel Standard and the Low Carbon Fuel Standard.[25]

For IL, IN, and IA, we consider only rain-fed corn, which accounted for more than 97% of total corn produced in those states in 2009.[26] For NE and KS, we separately analyze ethanol from rain-fed and irrigation corn. All corn grown in CA is irrigated.

3. METHODOLOGY

We developed an Excel-based model to estimate water requirements for corn and cob ethanol. The model is detailed in the Supporting Information, part I. In this section, we summarize the data sources and assumptions. The selected values are summarized in the Supporting Information, part II, while the rationale, assumptions, and sources are detailed in part I. Subject to data availability and applicability, the spatial scale (e.g., state versus county data) and temporal resolution (e.g., monthly versus annual averages) of key input parameters vary as outlined below and summarized in the Supporting Information, part I, Appendix A1.

3.1. Crop Water Requirements and Application Losses. We used the Food and Agriculture Organization's CROPWAT model V8.0 to calculate P_s and P_{os} for a total of 17 meteorological stations.[27] Climate data for these stations were taken from the CLIMWAT model V2.0, which gives monthly data averaged over a minimum of 15 years.[28] ET_a estimates for corn irrigation were based on statewide average applied water estimates from the 2008 Farm and Ranch Irrigation Survey (FRIS)[15] after adjustment for application losses based on the type of irrigation system and corresponding application efficiencies. The application efficiency is assumed to be 75% for furrow irrigation and 85% for the center pivot sprinkler system.[29,30] The former is the dominant system in CA and the latter in KS and NE.[15] Furthermore, we assume that 10% of the above inefficiencies are consumptive losses.[21,31−33]

We assume that percolation of excess irrigation water and precipitation before the crop season leach salts from the root zone and preclude the need to apply additional water for salt leaching; i.e., SL = 0.

3.2. Conveyance Losses. L_c accounts for 12% of total irrigation water withdrawn in NE[34] largely due to unlined canals,[35,36] with consumptive losses accounting for 1%. The corresponding figures for CA are 3.2% and 2.3%.[37] For KS, L_c is 4.3%,[34] the consumptive portion of which is assumed to be 1%.

3.3. Partitioning Water between the Grain and Cob. Since starch and cellulosic ethanol are treated differently in various regulatory policies, we calculate their water requirements separately. This necessitates partitioning of water used during corn cultivation between the grain and cob. Allocation methods based on mass, energy, or economic value are possible, although the system expansion/displacement method is generally preferred.[38,39] In this method, corn from the current system where both the corn and cob are harvested displaces corn from the reference system where the cob is incorporated back to the soil. Thus, the displacement method is equivalent to partitioning to the cob only the incremental environmental burden resulting from harvesting of the cob, while the entire baseline environmental burden ($P_s + P_{os} + ET_a + L_a + L_c$) is partitioned to the corn grain.[38−40] The incremental burden includes increased soil−water evaporation due to removal of biomass and an increase in fuel consumption, resulting in a corresponding increase in upstream water consumption. Given that the cob constitutes less than 20% of the mass of the stover, the moisture loss from cob removal may be ignored. The energy consumed to harvest the cob is 0.93 MJ/kg of cob.[38]

3.4. Ethanol from the Grain. For the corn grain ethanol pathway, we modeled dry mill conversion, which accounts for 88% of the operating capacity.[41] We assumed a yield of 10.56 L of undenatured ethanol/corn bushel[42−44] and a BR of 10.3 L/L of undenatured ethanol.[43] The biochemical conversion of corn

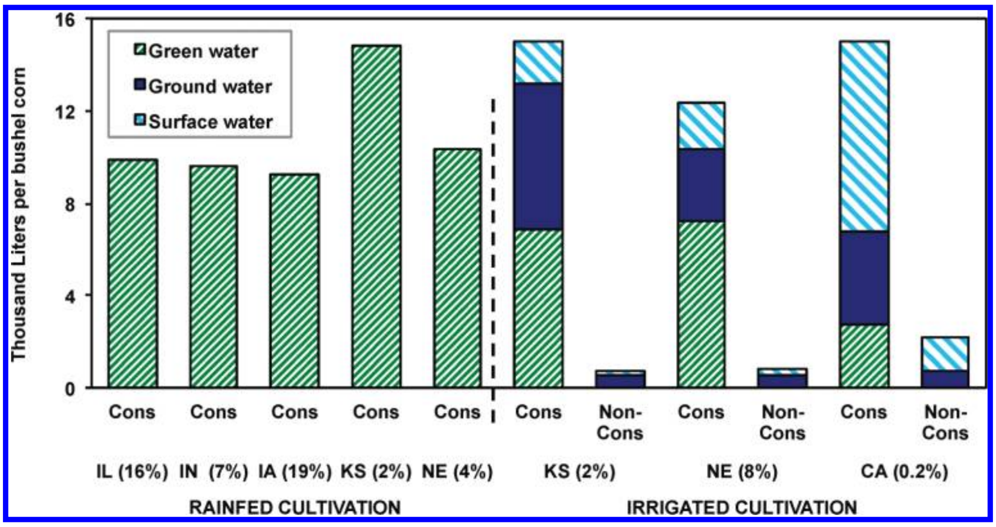

Figure 2. Water required for corn cultivation: consumptive use (Cons) and nonconsumptive water use (Non-Cons; water released back to the environment). The values in parentheses are the shares of corn produced in 2009.

grain to ethanol using dry mills also produces distillers' grain with solubles (DGS), which is used as an animal feed. DGS can substitute for other animal feeds—namely, corn grain, soybean meal (SBM), and urea.[39,45] SBM in turn displaces raw soybean.[39,42] Production of DGS precludes the need to produce other animal feeds; as a result corn ethanol should be credited for water saved from not producing them. The displacement ratios, which depend upon the relative nutrient content and market share of DGS and displaced products,[45] are based on GREET V1.8d[42] (Supporting Information, part I, Figure SI 3.2). We assume that displaced corn and soybean are grown in the same region (except for CA, where DGS displaces soybean from the U. S. Midwest) and are either rain-fed or irrigated depending upon the corn used for ethanol. Finally, we assume an average vehicle energy intensity of 3.88 MJ/VKT (Supporting Information, part I, section 2.4) on the basis of ref 46.

3.5. Ethanol from the Cob. Ethanol from the cob can be produced using either biochemical conversion (BC) or thermochemical conversion (TC). However, very few cellulosic conversion technologies are currently operating commercially, and data on ethanol yield and water consumption are uncertain. We have modeled the BC technology assuming an ethanol yield of 417 L/dry metric ton of cob and water consumption of 6 L/L of ethanol (Supporting Information, part I, section 3.5). Electricity demands during conversion are met internally through combustion of the lignin component of the cob, and the surplus—around 220 (kW h)/dry ton of cob—is exported to the grid. Surplus electricity displaces grid electricity, which has an average water intensity of 2.46 L/(kW h).[47]

3.6. Corn Yield. We use five year average corn yields for the agricultural districts in which the meteorological stations are located.[24] For NE and KS, ethanol from rain-fed and irrigated crops is analyzed separately, and we consider the respective yields. We assumed a cob/grain yield ratio of 0.18 where both the grain and cob are oven-dried (Supporting Information, part I, section 3.4). We also account for biomass shrinkage during storage and distribution of 1% largely due to microbial activity.[48]

3.7. Statewide Average Water Intensity. Water intensity estimates for various meteorological stations were averaged on the basis of corn production shares of the corresponding agricultural districts.

4. RESULTS

4.1. Water Requirements of Corn Harvested. Figure 2 summarizes the total water consumed for corn cultivation, separating rain-fed and irrigated cultivation in KS and NE. For IL, IN, and IA, the differences in GW consumption intensity are due to differences in yields, ET_c requirements, and supply constraints in the form of precipitation and available soil moisture. The difference in GW consumption intensity for irrigated and rain-fed corn in KS and NE reflects the large differences in yields; irrigated corn yields are 50−60% higher than rain-fed yields in KS and NE.[24,26] In KS, water was applied at a rate of 40 cm (1.6 million L/acre) for corn irrigation, which is 60% higher than in NE.[15] This explains the higher BW consumption intensity in KS despite the higher yield. Nonconsumptive water released to the environment is around 15% of the total water withdrawn in CA and 14% in NE and is attributable to inefficiencies of furrow irrigation in CA and the conveyance system (unlined irrigation canals) in NE. It is less than 8% in KS. Groundwater is the primary source of BW in both KS and NE, where it constitutes 60−80% of the water withdrawn.[49]

4.2. Water Intensity of Ethanol. The consumptive water intensity of grain and cob ethanol is shown in Figure 3. The BW intensity of ethanol from rain-fed corn is entirely due to BR and E_e and is the same (0.56 L/VKT) across all states. The BW intensity of ethanol from irrigated corn ranges from 50 L/VKT in NE to around 150 L/VKT in CA. The GW intensity of ethanol from rain-fed corn grain varies from around 70 L/VKT in IA to 135 L/VKT in KS. The low GW intensity of ethanol from corn grown in CA results from our treatment of coproduct credits: DGS produced in CA displaces high GW intensity soybean from the U.S. Midwest. Harvesting and converting the cob to ethanol reduces both the BW and GW intensities by 13%. Ethanol from the cob only (not shown in the figure) has a BW consumption intensity of 0.85 L/VKT, which is contributed from biorefinery water use, and zero GW requirements. Figure 3 also summarizes coproduct credits, which are around 5% and 45% of the total BW used to produce ethanol from rain-fed and irrigated corn, respectively, and around 50% of GW in both cases. The results reflect the lower yields and hence higher water intensity of soybean; for example, the statewide average applied water for

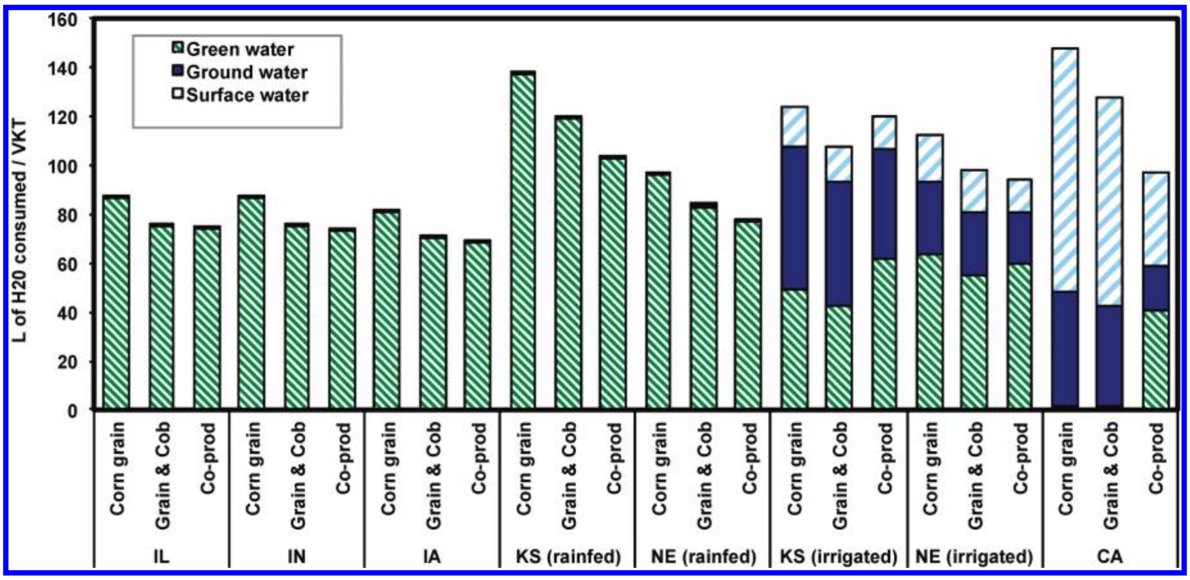

Figure 3. Water consumption intensity of ethanol from corn grain and crop residue and the avoided/displaced water use credits assigned to coproducts—DGS and electricity.

soybean was around three-quarters that of corn in 2008 in NE, but the average dry matter yield was less than 40% (Supporting Information, part II, Table SII 3.1). Also shown in Figure 3 is that DGS from the rain-fed corn pathway is displaced by rain-fed soybean, resulting in lower BW credits and vice versa.

Our results show that extending the system boundary to consider application and conveyance losses and the water requirements of embodied energy ($L_a + L_c + E_e$) increases the total BW withdrawal requirements by 23−38% and BW + GW consumption requirements by 5−16% (Supporting Information, part II). The E_e contribution is small, around 0.1−0.3 L/VKT; it constitutes less than 0.2% of the total BW intensity of ethanol from irrigated corn.

4.3. Impact on Statewide Water Demand. We estimated statewide water requirements for large-scale biofuel production. Ethanol production in each state is derived from the state's operating capacity and total U.S. ethanol production in 2009.[41] On the basis of the weighted average water intensity of ethanol from irrigated and rain-fed corn, aggregate water requirements were derived for each state (Supporting Information, part II, Table SII 4.5). BW consumed was compared with statewide irrigation water use[15] and industrial water use.[49] Without accounting for coproduct credits, 15−19% of irrigation water is used to produce the corn required for ethanol in the states of KS and NE and 8−10% after credits. Overall, around 6% of the total BW (after credits) is used to produce and convert corn to ethanol in KS and NE. In IL, IN, and IA, where corn is largely rain-fed, BW for ethanol production is less than 0.5% of the overall BW use. Though the volume of water use (BW withdrawal, BW and GW consumption) and the above comparisons with total consumption levels provide useful information for water resource management, caveats are discussed in section 5.

4.4. Average versus Marginal Analysis. Our water intensity estimates of ethanol are based on average water requirements of corn. Recent literature suggests that the marginal water requirements will be higher.[1] Higher corn prices, as a result of ambitious production mandates in the Renewable Fuel Standards,[50] could lead to expansion in corn production to marginal lands with lower yield potentials.[51] It could also result in intensification of corn cultivation in existing lands, which increases yield in the short run but could lower future yields.[52] Since water intensity is negatively correlated with yield, such expansion and intensification will increase the water intensity of ethanol. Further, corn expansion is occurring disproportionately on land that requires irrigation,[1,2] which according to our results has higher average total water (GW + BW) and BW consumptive intensities, as well as high nonconsumptive water requirements (Figure 2). Census data for 2002 and 2007 also provide evidence for such trends (Supporting Information, part II, Table SII 3.5). Future study could combine the methodology developed in this study with economic models to analyze the marginal impacts of ethanol production on water use.

4.5. Comparison with Fossil Fuel. The BW consumption intensityies of gasoline from conventional crude oil and Canadian oil sands range from 0.41 to 0.78 and from 0.29 to 0.62 L/VKT, respectively.[6] Water is required for crude oil recovery by water flooding, enhanced oil recovery via steam injection, and steam extraction of bitumen from oil sands and during refining of crude oil to produce gasoline. A recent U.S. Government Accountability Office report suggests the water intensity of gasoline from large oil shale deposits in the western United States could range from 0.29 to 1.01 L/VKT.[53] Gasoline's water requirements are summarized in the Supporting Information, part II.

Assessing the differences in water impacts of biofuels and fossil fuels is more complicated than simply comparing the total water intensities. The BW consumption of biofuels from rain-fed crops and residue is lower than that of gasoline, but orders of magnitude higher for those from irrigated crops. Ethanol from corn grain has a high GW requirement, and as discussed in section 1, GW use impacts terrestrial ecosystems and BW availability. Though the water intensity of fossil fuels is on average low compared with that of biofuels, it has been widely reported that oil sand production and potential shale oil development could result in substantial streamwater withdrawals and significant alteration of water flows during critical low river flow periods,[54] groundwater depletion and contamination, and wastewater discharges.[53,55] A detailed comparison of biofuel versus fossil fuel water use should examine the impacts of water use on changes in water availability and quality and other ecosystem health effects at the local and/or season scale, though such comparison is beyond the scope of our analysis.

5. DISCUSSION

Although we extended the system boundary to include additional water requirements, which increases the total BW withdrawal from 23% to 38% and BW + GW consumption from 5% to 16%, our estimates of corn grain ethanol's BW and GW consumption are lower than those of previous studies (Supporting Information, part II, Table SII 1.1). This is due to the accounting of coproduct credits for water use, which we estimated to be 5% and 45% of the total BW used to produce ethanol from rain-fed and irrigated corn, respectively, and around 50% of GW in both cases. It is interesting to observe that these numbers are higher compared with 20% of coproduct greenhouse gas (GHG) emissions credits estimated elsewhere.[39] This can be explained by the fact that soybean requires significantly less fertilizer and pesticides (which emit GHG),[42] but similar amounts of water compared to corn on a per bushel basis. As a result, dried DGS generates relatively less GHG emission credits but more water credits.

We estimated the water intensity of cellulosic ethanol using the displacement method, which assigns water use during corn cultivation entirely to corn. However, once the cob is established on a commercial scale, the cob will cease to be treated as an agricultural residue and the revenue potential of both the grain and cob will influence farming decisions. Under these circumstances, allocation based on economic value may then be more appropriate,[39] which will reduce the water intensity of grain ethanol but increase that of cellulosic ethanol. However, the weighted average water requirements and the sum, as represented in Figure 3, will remain the same.

The BW and GW requirements of ethanol from corn grown in different regions provide useful information for local water resource management; for example, water use by ethanol can be compared with a region's total water budget to identify potential water availability constraints and risks. However, such volumetric estimates do not consider differences in ecosystem or socioeconomic trade-offs as a result of differences in local hydrological conditions—specifically water "scarcity". Our method necessarily employs *spatial* and *temporal* aggregation. It sums across types of water consumption (BW and GW consumption and *avoided* water credits) in locations where the relative importance of water-related aspects may differ; thus, some results may carry no clear indication of potential social and/or environmental harm or trade-offs.[10] Similarly, temporal aggregation of water use estimates ignores the interseasonal variability of water use and water scarcity and can therefore yield erroneous conclusions concerning seasonal water use competition. Recent literature on freshwater LCA has developed regionally differentiated characterization factors that measure water scarcity at a watershed level[9] and also account for temporal variability in water availability.[10] Volumetric estimates of GW and BW may be converted using characterization factors to provide "stress-weighted" or "ecosystem-equivalent" water footprint estimates that can be compared across regions. Work is ongoing to use the explicit water inventory results to undertake impact analysis and accurately assess the effects of biofuel production on water resources.

ASSOCIATED CONTENT

Supporting Information. Detailed documentation of water requirements, methodology, assumptions, and data sources (part I), literature review, summary of key inputs, and detailed results (part II), and Excel-based model. This material is available free of charge via the Internet at http://pubs.acs.org.

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