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Water consumption estimates of the biodiesel process in the US

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Abstract As a renewable alternative to petroleum diesel, biodiesel has been widely used in the US and the world. However, its potential impact on water resources has not been much evaluated. This study investigates water consumption from the biodiesel process, which includes three stages: soybean irrigation, soybean-to-soybean oil processing, and biodiesel manufacturing, at both national and state levels. Mass-based allocation is performed and water consumption at the three stages is obtained on the basis of million gallons per year and gallon water per gallon biodiesel (gal/gal). The normalized water consumption (water intensity) of the irrigation, oil processing, and biodiesel production stages are 61.78, 0.17, and 0.31 gal/gal, respectively. The resulting total normalized water consumption is 62.26 gal/gal for the biodiesel process which is much lower than those reported in existing literature. It is shown that water consumption from the three stages varies significantly from state to state, which warrants the necessity of state-level water consumption analysis for better decision making in water resources management. Water consumption in potentially water-stressed states is also investigated and results show that currently these states represent 1.6 % of total water consumption associated with biodiesel production, 0.46 % of soybean harvest, and 27.61 % of biodiesel production capacity in the US.

Keywords Biodiesel · Water consumption · Irrigation · Soybean crushing and processing · Water-stressed areas

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Introduction

As one of the commercially successful renewable fuels in the market, biodiesel possesses several desirable benefits: reducing the emissions of most criteria air pollutants (e.g., SO_2 and CO), decreasing the reliance on fossil fuel consumption and prompting energy independence. (Agnew et al. 2009; Ng et al. 2010; Jindal and Goyal 2012). The US biodiesel industry has grown rapidly in recent years. In 2012, approximately 1.1 billion gallons of biodiesel were produced from 193 biodiesel manufacturers comparing from 28 million gallons in 2004 (NBB 2013). Currently soybean remains the dominant biodiesel feedstock in the US, although the shares of other feedstocks, such as canola and waste cooking oil, are on the rise (Schill 2008). Based on the estimates from United States Department of Agriculture (USDA), approximately 17 % of total soybeans harvested were consumed for methyl ester production in 2007 (Centrec Consulting Group 2010). The expansion of biodiesel industry, however, also comes with concerns, such as the food versus fuel debate, land use change, and increased demands on water resources. If not addressed properly, these concerns can negatively impact the sustainability of the biodiesel industry in both near and long terms.

Among various life cycle water consumption studies on biodiesel, the following are relevant to this study. King and Webber (2008) performed a life cycle study on water intensity of selected transportation fuels. For irrigation water use, the data used include irrigation data from "USDA 2003 Farm and Ranch Survey" and irrigation loss data from a USGS report (Solley et al. 1998). Three irrigation scenarios were considered and the overall water consumption involved indirect water usage, such as energy generation-related water consumption, and water consumptions in other stages. The overall water intensity of biodiesel produced from irrigated soybean, which is 0.6–24 gal water/mile (1.4–56.7 L/km), based on a fuel efficiency of 25.7 miles per gallon (mpg) for the light duty vehicles (LDV). The US average from their study is 12 gal water/mile (28.4 L/km). If the soybean was not irrigated, the water use is 0.01–0.02 gal water/mile (0.02–0.05 L/km). Harto et al. (2010) studied water consumption for soybean biodiesel from life cycle perspective, and the overall water consumption is 131 gal water/gal biodiesel ("gal/gal" hereafter). Similar to King and Webber, O'Connor also used USDA reports for irrigation water intensity of soybean biodiesel (O'Conner 2010). At a national average irrigation ratio of 8.2 % (USDA 2007), the national average irrigation water consumed is approximately 79 gal/gal, much lower than other studies. Mulder et al. (2010) calculated water consumption of the biodiesel supply chain based on market value of co-products and mass fraction of biodiesel in the final products. The resultant biodiesel water use is 21.81 L/MJ, equal to 719.98 gal/gal. More details on the parameters and assumptions used by these studies are summarized in Table S6 in the supporting material for results comparison with this study.

These studies only estimated biodiesel water use at the national level, which did not consider substantial variations among 50 states, as shown in this study. In addition, the existing studies did not take into account that only a fraction of soybean oil was used for biodiesel production every year (Lee 2011; Pimentel and Patzek 2005). As an example, only 17 % of soybeans harvested were processed into biodiesel in 2007 (Centrec Consulting Group 2010), which made a significant difference in the estimation of total water consumption for biodiesel production.

In this study, the term biodiesel process includes the following three stages: soybean growth, soybean processing to soybean oil, and biodiesel manufacturing. Water consumption was estimated by using characteristic allocation factors for each of these three stages. State-level estimations of water consumption were presented as well as the national average values.

Methodology

Water consumption in the biodiesel process is estimated as the sum of irrigation water use (W_1) in soybean growth stage, water use during soybean crushing and processing into soybean oil (W_2), and water use in biodiesel production (W_3). Both W_1 and W_2 focus on soybean due to its dominant market share in biodiesel production in the US as well as data availability. W_1, W_2, and W_3 are expressed in the unit of "million gallons per year (MGPY)". N_1, N_2, N_3 are the normalized values for each stage based on biodiesel produced in the unit of "gallons of water per gallons biodiesel (gal/gal)", which are commonly used by other studies. The parameters for state-level water consumption are expressed as W_{1j}, W_{2j}, and W_{3j}, with j representing each state. The overall total water consumption for the US W_{tot} is the sum of W_1, W_2, and W_3, and corresponding normalized value N_{tot} is the sum of N_1, N_2, and N_3. Details in estimating of W_{1j}, W_{2j}, W_{3j}, N_{1j}, N_{2j}, and N_{3j} for Ohio are provided in ESM Appendix 1–3. A nomenclature of all the terms can be found in ESM Appendix 7. Allocation was performed based on the mass portion of the co-products obtained at the end of each stage, as indicated from many of the existing LCA studies (López et al. 2010; Talens Peiró et al. 2010; Pradhan et al. 2011; Dufour and Iribarren 2012; O'Connell et al. 2013).

Data sources

Soybean irrigation stage: irrigation water consumption (W_{1j}, N_{1j})

The "Farm and Ranch Irrigation Survey" (2008 as the most current) is used in this study since the USDA surveys are considered representative for the irrigation water in soybean growth sector (USB 2010; USDA 2008). In estimating W_{1j}, the following factors have been considered: the portion of the soybean processed into biodiesel, the oil content of soybean grain, biodiesel and the efficiency of the transesterification reaction. Due to the lack of sufficient data, indirect water consumption such as water consumed during fertilizer production and water use for energy generation are not included in this study. In addition, water loss factor is not accounted for during the irrigation stage, i.e., irrigation water input during the irrigation is assumed as 100 % consumptive.

Soybean processing stage: crushing and extraction, crude oil refining (W_{2j}, N_{2j})

After harvest, the soybean is transported to the refining plant for crushing, oil extraction, and crude oil degumming. Water consumptions in this stage are mainly equipment operation related, such as cooling tower makeup or water use in free fatty acid (FFA) removal (USB 2010; Van Gerpen et al. 2004). The FFA is usually removed from soybean oil via caustic refining, i.e., neutralize the FFA with a caustic soda and use water to wash away the soap formed. Other refining practices, such as bleaching and deodorizing are not as considered at this stage since they are less typical.

Water consumption involved in this stage was summarized in an aggregated form by the National Oilseed Processers Association (NOPA), which was the result of a representative survey among its member companies in 2008 (USB 2010).

Biodiesel production stage: crude biodiesel purification, cooling tower makeup (W_{3j}, N_{3j})

In biodiesel manufacturing stage, the following processes are found to be associated with water use: biodiesel wash to remove residual glycerin and other impurities, cooling tower makeup, and boiler makeup. The actual consumption can vary considerably depending upon the system setup and the extent of heat economization used in the facility (Scott 2010; Smith 2011). Due to the pretreatment requirement of the wash water before discharge, dry wash technologies nowadays are increasingly practiced by biodiesel producers to replace the traditional water wash. Even for water wash, the wash water is reused instead of discharging after one use. Boiler water makeup should be considered when distillation is used to separate glycerin from biodiesel, and the rates vary dependent on the distillation processes (vacuum or steam distillation) used in the facilities. The resultant boiler water makeup from vacuum distillation can be much lower than steam distillation. The cooling tower makeup should be considered in W_3 if the producer uses evaporative cooling towers to condense process vapors (such as for methanol recovery) and cool liquid process streams. In this study, these data are collected from the actual biodiesel producers in addition to literature. Out of these parameters, the irrigation ratio soybean harvest, and biodiesel production capacities have also been analyzed in "Results" section to better understand water consumption of the biodiesel process in each stage and in each state.

States reporting zero water use

The following 15 states: Alaska, Arizona, California, Florida, Hawaii, Idaho, Montana, Nevada, New Hampshire, New Mexico, Oregon, Pennsylvania, Rhode Island, Utah, and Wyoming are not included in the calculation of W_{1j} and N_{1j}, either due to negligible soybean growth or lack of irrigation data from the USDA report. For the W_{2j} and N_{2j} estimate, only 12 states are left out either due to no soybean growth or data deficit (States of Alaska, Arizona, California, Hawaii, Idaho, Nevada, New Hampshire, New Mexico, Oregon, Rhode Island, Utah, and Wyoming).The states of Florida, Montana, and Pennsylvania have soybean harvest data although irrigation data are not available (not reported as "zero").

Four states are not included in the calculation of W_{3j}, total and normalized water consumptions during biodiesel manufacturing stage (Colorado, Montana, Vermont, and Wyoming) since there are no biodiesel production in those states upon the closure of this study.

Results

Water consumption in soybean growth stage (W_{1j}, N_{1j})

Figures S1 and S2 show the results of irrigation water consumption (W_{1j}) and irrigation water intensity (N_{1j}) for soybean dedicated to biodiesel production of 35 states. While W_{1j} is a direct reflection of the irrigation water consumption, N_{1j} is an insightful measurement of irrigation intensity regardless of the soybean growth scale for the specific state. The irrigation water use W_{1j} varies significantly from state to state, from zero to 15, 953.00 MGPY. The range of normalized irrigation intensity (N_{1j}) varies from 1058.20 gal/gal (Washington) to 0.00 gal/gal (states with minimal irrigation) with a weighted nationwide average (N_1) of 61.78 gal/gal.

The states with negligible irrigation consumption (0.00 MGPY) are Massachusetts, Connecticut, Maine, Vermont, West Virginia, and New York due to limited soybean growth. In fact, Massachusetts, Connecticut, Maine, Vermont, West Virginia, and New York rank at 35, 34, 33, 31, 29, 23th in terms of total amount of soybean harvested. On the other hand, the states at the highest irrigation water use, Arkansas (15,953.00 MGPY), Nebraska (9056.78 MGPY), Mississippi (3714.78 MGPY), Kansas (2514.84 MGPY), and Missouri (2456.94MGPY), are also major soybean producers, ranking at 10, 6, 14, 11, and 7th among the 38 states that reported soybean harvest.

The irrigation intensity of 11 states: Washington, Arkansas, Colorado, Mississippi, Nebraska, Texas, Delaware, Kansas, Louisiana, Georgia, and Oklahoma are above the national average, with values of 1058.20, 674.30, 611.52, 285.90, 199.74, 190.08, 148.21, 127.09, 108.59, 106.75, and 88.13 gal/gal, respectively. These 11 states represent 18.32 % of total soybean harvest and 36.10 % of total biodiesel production capacity. In tandem with the findings from previous discussion, Arkansas (134.59 gal/gal), Mississippi (650.67 gal/gal), and Nebraska (1821.6 gal/gal) are the three states with both significant soybean growth and irrigation water consumption. Although the states of Washington and Colorado have very high irrigation intensities, their total irrigation water consumptions (W_{1WA}, W_{1CO}) are lower than the national average due to much less soybean cultivation.

On the other hand, Iowa, Illinois, Minnesota, Indiana, and Ohio account for 56.37 % of US soybean production while their irrigation water intensities are only 1.88, 4.01, 8.60, 7.85, and 0.71 gal/gal, respectively. The much lower N_{1j} values reported in states such as Illinois, Indiana, Iowa, Kentucky, Minnesota, North Dakota, Ohio, South Dakota, and Tennessee, are due to much less irrigation used in soybean production in these states.

A main contributing factor to the wide range of state-level irrigation water intensities is the vastly different irrigation ratios (irrigated acres vs. total acres). The average irrigation ratio is 8.2 % among these 35 states, with the range of 0–65.40 % (Arkansas), and 25 states have irrigation ratios below average. For the top five soybean producing states, soybean irrigation ratio ranges from 0.02 to 1.72 %. These results indicate that it may be advantageous to grow soybean where irrigation is less needed rather than states that have high irrigation ratio. Due to the significant variation in irrigation practices among the states, a simple national average cannot accurately represent water use in the US.

Water consumption in soybean processing and refining stage (W_{2j}, N_{2j})

A uniform value of N_2 (0.17 gal/gal) is used for calculation (ESM Appendix 2) and the range of W_{2j} varied from 0.003 to 112.00 MGPY.

Water consumption in biodiesel production stage (W_{3j} and N_{3j})

Water consumption data in biodiesel washing vary significantly in existing studies. The National Biodiesel Board (NBB) estimated that one pound of wash water was needed for four pounds of biodiesel, which is equivalent to 0.22 gal/gal (Scott 2010). The United Soybean Board conducted a life cycle assessment for the soybean-to-biodiesel process, where water used for biodiesel washing was reported as 0.26 gal/gal (USB 2010). However, water consumption from simulations are 0.03 (Haas et al. 2005) and 0.01 gal/gal (Zhang et al. 2003), respectively.

The substantial difference in water use among data sources warrants data collection from the actual biodiesel manufacturers. In this study, inquiries were sent to 123 commercial biodiesel producers listed under NBB. 21 replies were received, among which six reported water washing, 11 indicated dry purification and four considered this information proprietary. The weighted average water consumption based on plant capacity is 0.12 gal/gal in biodiesel washing (company details in Table S3). Therefore, water consumption in biodiesel wash is determined as a range from 0.12 to 0.26 gal/gal, and 0 gal/gal for dry wash.

Cooling tower makeup water

The dry wash method often consumes less water during distillation as compared with water wash, which may be due to the increased water evaporation when distilling recycled water. Water consumption for cooling tower makeup is presented in Table S4. This once again indicates the highly process-specific characteristics of actual biodiesel operations. The water consumption of cooling water makeup is averaged based on plant capacity, and is also separated as the dry and water wash.

Accordingly, the cooling tower makeup for these two scenarios is 0.275 gal/gal, with 0.153 gal/gal for dry wash. No information is available on boiler water makeup and the extent of dry wash use among biodiesel producers.

The water consumption rates in biodiesel production (N_3) are summarized based on three scenarios: water wash (upper range), water wash (lower range), and dry wash with the corresponding values for N_3 being 0.54, 0.4 and 0.15 gal/gal, respectively. On average, dry wash consumes approximately one third of water in the biodiesel manufacturing process. A uniform N_3 of 0.31 gal/gal is calculated by averaging the three scenarios. Accordingly, the resultant water consumption in biodiesel production (W_{3j}) is estimated based on N_3 and biodiesel capacities in each state (Biodiesel Magazine 2013).

The biodiesel production capacities in the 46 biodiesel producing states vary from 0.25 MGPY in Alaska to 577.25 MGPY in Texas. With the assumption that the purification and process water consumption rate (N_3), 0.31 gal/gal (ESM Appendix 3) is uniformly applied to all these biodiesel plants, the resultant W_{3j} ranges from 0.08 to 178.47 MGPY. As dry wash technologies are increasingly practiced among the biodiesel industry, the water consumption of this stage is expected to decrease with time (Dugan 2007).

The total annual water consumption by states ($W_{tot,j}$, $N_{tot,j}$)

The total quantity (W_{tot}) of consumptive water as the sum of water consumption from three stages is summarized for each state as the sum of water consumption in irrigation (W_1), soybean-to-soybean oil processing (W_2), and biodiesel production (based on capacity, W_3). The fractions of water use at each stage are also estimated to better understand the relative contribution. Figure 1 illustrates the total consumptive water ($W_{tot,j}$) for the soybean-to-biodiesel process in each state. 49 states are included in this figure with the exception of Wyoming which has neither soybean growth/processing nor biodiesel plants in 2007/2008. $W_{tot,j}$ ranges from 0.004 MGPY to 16,016.11 MGPY in these 49 states. Figure 2 shows the normalized total water consumption for 49 biodiesel producing states. The range of $N_{tot,j}$ varies from 0.17 to 1058.68 gal/gal, with a national average of 62.26 gal/gal. On average, irrigation represents 99.40 % of the total water consumption, 0.21 % for soybean crushing/refining, and 0.39 % for biodiesel manufacturing. However, the fractions vary significantly among the states.

Water consumption for the ten states with the highest soybean harvest is listed in Table 1. These represent 83.31 % of soybean harvest in the US. Most of these major soybean growing states are located in the Midwest region with the exception of Arkansas. The irrigation intensities (N_{1j}) of these states are below national average with the exception of Arkansas, Nebraska and Missouri. This again supports the fact that not all soybeans in the US are irrigated, and warrants state-level water consumption analysis.

Table 2 lists water consumption situations in the ten states with the highest biodiesel capacities. These ten states account for 66.6 % of biodiesel production capacities in 2013 (Biodiesel Magazine 2013), and their normalized total water consumption $N_{tot,j}$ are 190.56, 2.36, 62.37, 4.49,1.19, 8.33, 674.78, 286.37, 1058.68 and 0.31 gal/gal, respectively. The States of Arkansas (#1 in irrigation water use), Mississippi (#3), Missouri (#5), Indiana (#8), Illinois (#9), and Iowa (#14) are both the highest in irrigation water use (not necessarily soybean production) and biodiesel production. This may be an indication that the soybeans produced have been consumed in close proximity, as biodiesel plants usually seek the feedstock nearby to reduce the cost of transport and storage.

In contrast, water use from biodiesel production has much larger fractions in the states of Washington and Pennsylvania comparing with soybean irrigation as soybean growth in these states is relatively low.

It is noteworthy that in most of the states, W_{1j} and W_{3j} dominate the total water consumption for biodiesel production except for Ohio, Illinois, and Iowa where W_{2j} consumptions account for 28.04, 19.02, and 40.53 % of water use in their biodiesel processes, respectively. This is due to high soybean harvest (5th, 2nd, and 1st in the US) and therefore high percentage of water use in soybean oil processing.

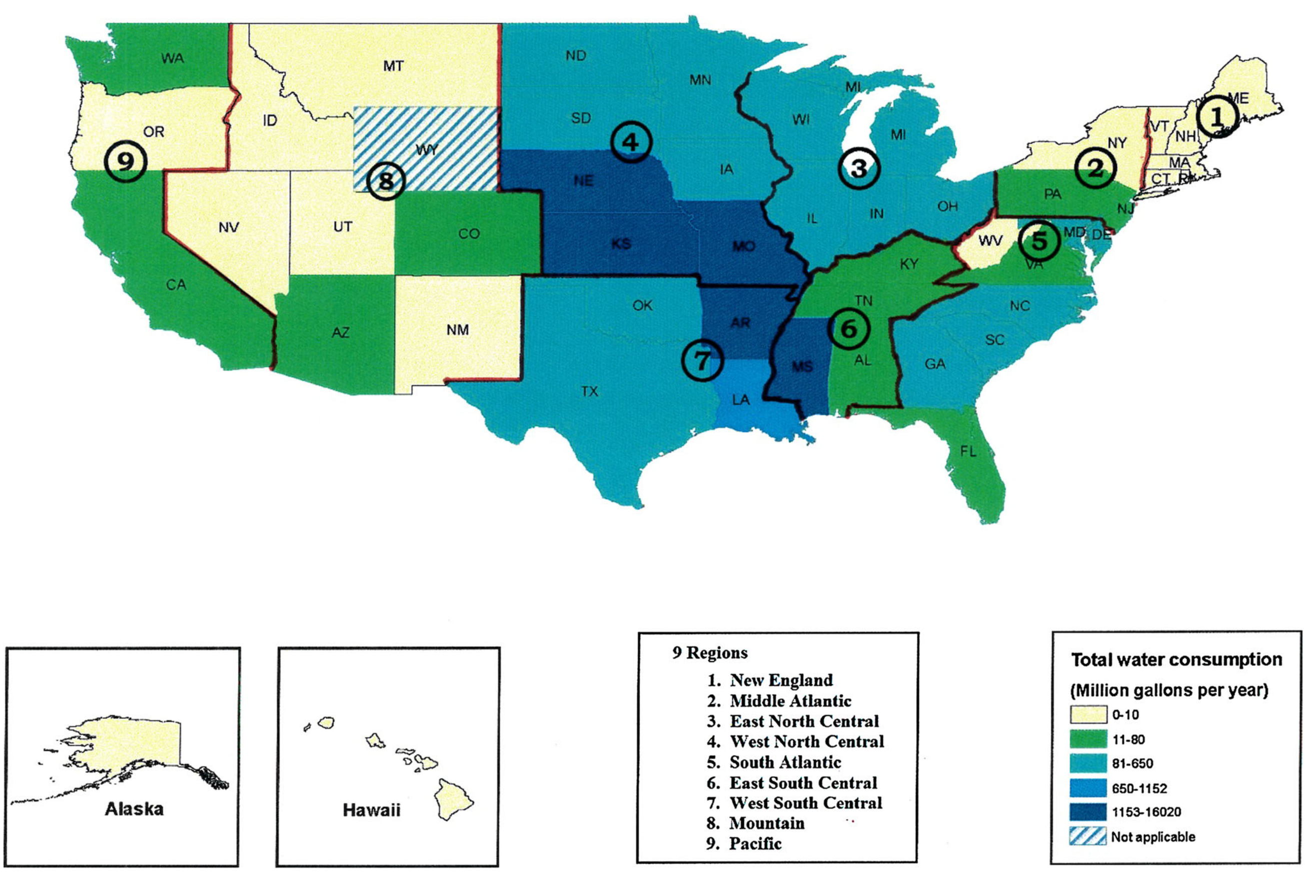

Fig. 1 Total annual water consumption of the soybean-to-biodiesel process ($W_{tot,j}$)

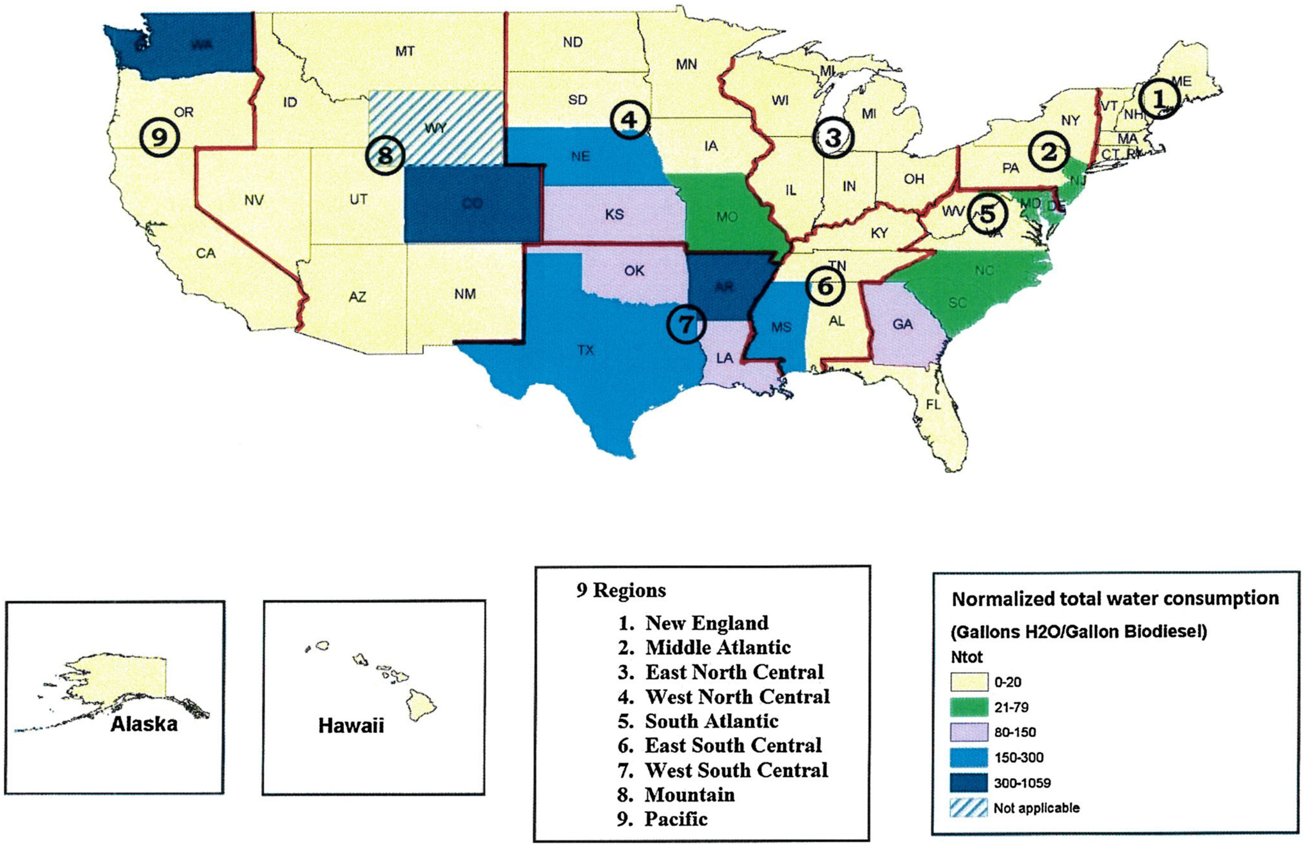

Fig. 2 Total water consumption of the soybean-to-biodiesel process on per gallon biodiesel basis ($N_{tot,j}$)

Table 1 Total annual water consumption ($W_{tot,j}$) in top 10 soybean harvesting states (ranked by harvest)

State	$W_{tot,j}$ (MGPY)	$W_{1j}/W_{tot,j}$ (%)	$W_{3j}/W_{tot,j}$ (%)
Iowa	400.577	48.46	23.50
Illinois	484.8529	69.91	11.07
Minnesota	622.8166	85.84	3.28
Indiana	488.7905	81.09	7.65
Ohio	123.2441	26.36	33.11
Nebraska	9107.751	99.44	0.02
Missouri	2556.946	96.09	2.22
South Dakota	289.2936	87.50	0.75
North Dakota	139.1979	60.49	19.55
Arkansas	16,016.11	99.61	0.23

Table 2 Total annual water consumption ($W_{tot,j}$) in top 10 biodiesel producing states (ranked by plant capacities)

State	$W_{tot,j}$ (MGPY)	$W_{1j}/W_{tot,j}$ (%)	$W_{3j}/W_{tot,j}$ (%)
Texas	335.77	45.58	53.16
Iowa	400.58	48.46	23.50
Missouri	2556.95	96.09	2.22
Illinois	484.85	69.91	11.07
Ohio	123.24	26.36	33.11
Indiana	488.79	81.09	7.65
Arkansas	16,016.1	99.61	0.23
Mississippi	3764.65	98.68	0.95
Washington	41.98	16.75	83.23
Pennsylvania	34.85	0	98.70

Discussion

Regional impact analysis

In this study, regional water use for the biodiesel process is also analyzed by grouping the states into nine census regions (ESM Appendix 5, Dodder et al. 2011). Table 1 indicates that nine out of the ten highest soybean growing states are in the East North Central and West North Central regions, except Arkansas in West South Central. With high soybean harvest, the states of South Dakota and North Dakota are below the national average in irrigation water use and total water use, which suggests that these states may have the potential to increase biodiesel production in order to take advantage of local feedstock.

In Table 3, water consumption of the biodiesel process for each region is evaluated by the fractions of irrigation (P_1) and biodiesel manufacturing (P_3), and also the regional irrigation intensity ($N_{\text{tot-region}}$).

The West South Central (TX, OK, AR, and LA) has the largest water consumption, 43.35 % of the total water consumption, and 5.13 % of soybean harvest, the 3rd highest in the US. State-level data indicate that the high water consumption is mainly caused by the higher than average irrigation intensities in AR, LA, and OK and large biodiesel production capacity in Texas. West North Central is the second largest in water consumption, representing 39.65 % of the total water consumption but low total water intensity. The region represents 53.25 % of soybean growth and 22.5 % of biodiesel capacity. New England region (six states) accounts for approximately 0.01 % of the water consumption in the US and is predominantly from biodiesel manufacturing. Similar trend can be found in the Pacific and Middle Atlantic regions. The highest regional water intensity in the Pacific region is due to the irrigation water intensity in Washington, which is the highest. Together with Figs. 1 and 2, it is indicated that the water use in this region is vastly different. In addition, regional heterogeneity is also evident for the West South Central, East South Central, and South Atlantic Regions.

It is found that regional data tend to average out differences among the states. Therefore, from planning and decision-making standpoints, state-level data can be more accurate than regional.

Water-stressed areas

For areas where water supply is potentially in constraint, the impact of the biodiesel process on water resources should also be analyzed for future climate adaptation considerations. A few studies have identified the water-stressed areas based on different criteria as summarized in Table S5. A detailed report on these studies is provided in supplemental materials (ESM Appendix 4). Integrating results from Table S5, the following states are identified as water stressed in this study: Arizona, California, Colorado, Florida, Georgia (Southern Georgia), New Mexico, Nevada, and Texas (Western Texas). Accordingly, a summary of total annual water consumption ($W_{\text{tot},j}$) is found in Table 4.

These states represent 1.6 % of total water consumption associated with biodiesel production, 0.46 % of soybean harvest, and 27.61 % of biodiesel production capacity in the US. For the States of California, Arizona, Florida, New Mexico and Nevada, more than 99 % of their water consumption associated with biodiesel production process is accounted for by the biodiesel manufacturing stage, due to very limited soybean growth in these areas. Colorado and Georgia only account for 0.32 % of the total soybean harvested and 0.63 % of total water consumption associated with biodiesel production in the US, however, the irrigation intensity in Colorado is 611.52 gal/gal, the 3rd highest in the US, while Georgia ranks the 10th with irrigation water intensity of 106.8 gal/gal. Texas accounts for 0.13 % of total soybean growth and 19.71 % of biodiesel production capacity in the US while its irrigation water intensity of 190.58 gal/gal, the 6th highest in the US.

For companies located in water-stressed areas, such as Company 2 (Table S3) in West Texas and Company 4 in California, adoption of water saving technologies may be more critical. If biodiesel productivity is to expand in these areas, water supply issues should be considered in the decision-making process.

Comparison with existing studies

Table S6 provides a detailed comparison of this study with other similar studies by evaluating different parameters and assumptions used in these studies. Different units used by other studies are converted to gal/gal basis for comparison (ESM Appendix 6). In the soybean growth stage, all studies except King and Webber (2008) assumed a complete consumption of irrigation water, i.e., none of applied irrigation water was recycled or reused. Different irrigation

Table 3 Regional water consumption data

	W_{tot} (MGPY)	P_1 (%)	P_3 (%)	$N_{\text{tot-region}}$ (gal/gal)
New England	4.22	0.00	99.25	0.48
Middle Atlantic	60.95	23.73	73.10	8.65
East North Central	1617.51	76.11	9.73	6.34
West North Central	15,654.20	96.43	1.30	46.68
South Atlantic	981.66	90.32	7.74	51.86
East South Central	3892.92	97.35	1.94	149.77
West South Central	17,114.78	98.44	1.36	535.59
Mountain	42.16	51.50	48.40	551.62
Pacific	71.78	9.80	90.19	1058.68

Table 4 Total annual water consumption ($W_{tot,j}$) for the states in water-stressed areas

State	$W_{tot,j}$ (MGPY)	$W_{1j}/W_{tot,j}$ (%)	$W_{3j}/W_{tot,j}$ (%)
Arizona	14.84	0	100
California	24.26	0	100
Colorado	21.75	99.82	0
Florida	12.13	0	99.46
Georgia*	225.24	90.36	8.72
New Mexico	0.46	0	100
Nevada	0.31	0	100
Texas*	335.77	46.58	53.16

* Only southern GA and western TX have been reported as water-stressed areas

ratios were used in these studies. This study is consistent with O'Connor (2010) in irrigation water intensity and its water intensity in biodiesel manufacturing (N_3) is in the same range as King and Webber (2008) and Harto et al. (2010). As agreed by all the studies, the water intensities in soybean oil processing and biodiesel manufacturing are much smaller than irrigation water intensity.

O'Connor (2010) used an overall irrigation ratio of 8.2 % by dividing irrigated acres of soybean over total harvested acres. King and Webber (2008) separated the calculation by either non-irrigation or 100 % irrigation scenarios. Harto et al. (2010) averaged the irrigation ratios from low, middle, and high cost soybean farms and the national average was 4 %. Irrigation ratio was not specified in (Mulder et al. 2000). Only King and Webber (2008) and this study quantified water intensity during soybean processing stage (N_2). For biodiesel manufacturing stage (N_3), both King and Webber (2008) and Mulder et al. (2010) cited data from Sheehan et al. (1998) and their values were 0.158 and 3.63 gal/gal, respectively. Harto et al. (2010) used 1 gal/gal from a 2006 DOE report (US DOE 2006). In this study, N_3 comes from more reliable sources, such as the actual biodiesel industry, the NBB, and the United Soybean Board. For the actual water use in "million gallons per year (MGPY)", the values obtained in this study are expected to be much lower than others since only 17 % of the soybean oil were processed into biodiesel. Substantial data variation exists among individual states, which is an indication that state-level data can be more accurate than both the national average and the regional data.

Generalization of the study approach

Although data are acquired in the US, the study approach can be generalized for other countries and regions having significant geological and climate variations. Water consumption from biofuel plant growth tends to be the highest among the life cycles of biofuels harvested from agricultural processes. Therefore, data accuracy at this stage is essential to the overall biofuel water footprint estimation. Instead of a national average, more detailed data should be sought, such as state/provincial levels, so that the variations among the states/provinces are not averaged out. Different practices of irrigation among different regions should be taken into account. In addition, the fraction of the feedstock that is actually processed into a biofuel should be considered. As an example, in the US, only 17 % of the soybean oil was made into biodiesel. This study also provided information on data sources and organizations where such data may be available. For potentially water-stressed areas in the US and around the world, water conservation technologies should be advocated. If a biofuel production is to expand in such regions, water supply and demand should be carefully studied. Water consumption results from this study can be included in the life cycle analysis of biodiesel processes, especially at the state level. This can serve as a base case water consumption analysis for the soybean biodiesel process in the US, to be compared with future studies with new data and technology innovations.

Limitations of the current study

1. Although only west Texas and southern Georgia are considered water-stressed areas instead of the whole states, data are only at state level, so the estimates in Table 4 are for the entire states. In estimating of W_2 and W_3, uniform allocation factors have been used, instead of using state-specific allocation factors due to data limitation. For W_3, the 0.31 gal/gal may decrease as dry wash is increasingly adopted by biodiesel manufacturers.
2. Indirect water consumption (e.g., water consumed during fertilizer production and water use for energy generation) was not included in this study. It is also assumed that irrigation water input during the irrigation is 100 % consumptive.
3. In the real-life situation, some biodiesel producers may import soybean oil from other states to meet the demand, especially those in the states where soybean growth is minimal (e.g., CA and WA). The introduction of the imported soybean oils may change the N_{1j} of the biodiesel produced in the specific state, since usually there is a significant difference in the irrigation application between states. Considering the fact that major soybean producing states such as IA and OH have more than enough soybean oil available to meet the demand for in-state biodiesel production, it is likely

that the export of soybean oil from these states may help reduce the N_{1j} of the soybean biodiesel in other states. To quantify this phenomenon, robust data are need for the record of soybean oil trade across the boundary of states for biodiesel production. Unfortunately, such a data set is not yet available to the best of authors' knowledge.

Conclusions

Water consumption associated with biodiesel production from soybean mainly consists of soybean irrigation, oil processing, and biodiesel manufacturing stages. The findings from this study indicate that on average irrigation water consumption accounts for 61.78 gal/gal while water consumption in soybean oil processing and biodiesel manufacturing is 0.17 and 0.31 gal/gal, respectively. Significant variations in water consumption are found among the states, which are mainly due to irrigation practices and the capacity of biodiesel manufacturing.

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