**Supporting Information for the Manuscript:**

Water Consumption Estimates of the

Biodiesel Process in the US

*Qingshi Tu, Mingming Lu, Y. Jeffrey Yang*

**19 pages total:**

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**Table S1.** **Data used for sample calculation in Ohio**

|  |  |  |  |
| --- | --- | --- | --- |
| Parameters | Value | Unit | Reference |
| Irrigation intensity | 3.2 | Acre-feet/acre | **2008 Farm and Ranch Irrigation Survey**14 |
| Irrigated area | 1,056 | Acre | 2007 Census of Agriculture9 |
| Soybean harvested | 191,559,567 | Bushel | 2007 Census of Agriculture9 |

**Table S2.** Water consumption during soybean processing and refining stage

|  |  |  |
| --- | --- | --- |
| Process | Water(kg/1000 kg soybean oil) | Reference |
| Processing (crushing, extraction & degumming) | 1,164 | United Soybean Board13 |
| Refining (caustic refining) | 65.9 | United Soybean Board13 |

**Table S3.** Water consumption data in biodiesel wash collected from biodiesel manufacturers

|  |  |  |  |
| --- | --- | --- | --- |
| Data Sources | Feedstock | Washing Water (gal/gal) | Production Capacity(Million Gallons per year ) |
| Company 1 | Multi-feedstock | 0.1 | 3 |
| Company 2 | Animal Fats | 0.0125~0.015 | 1.25 |
| Company 3 | Waste Cooking Oil | 0.84 | 4.5 |
| Company 4 | Multi-feedstock | 0.25~0.375 | 12 |
| Company 5 | Multi-feedstock | 0.09~0.1 | 180 |
| Company 6 | Waste Cooking OilAnimal Fats | 0.06 | 1.5 |

\* Company names omitted at their requests.

The variation in the data reported by these companies can be attributed to a number of factors, including water reuse practices, washing water properties (e.g. acidic/warm), plant size, as well as water availability and pricing.

**Table S4.** Water consumption in cooling tower makeup

|  |  |  |  |
| --- | --- | --- | --- |
| Data Sources | Feedstock | Purification method | gal water/ gal biodiesel |
| Company 7 | Virgin oil | Dry wash (silicate) | 0.12-0.15 |
| Virgin oil | Water wash with recycle | 0.19-0.21 |
| Waste cooking oil | Dry wash (silicate) | 0.27-0.3 |
| Waste cooking oil | Water wash with recycle | 0.33-0.36 |
| Company 8 | Multi-feedstock | Dry wash (silicate) | 0.03-0.05 |

Data from Company 7 indicates that using low quality feedstock corresponds to higher makeup water, which may be due to the need to recover excessive amount of methanol (e.g. for the esterification reaction). Company 8 has much smaller makeup water consumption, which is achieved by integrating other cooling approaches such as an air chiller. The biodiesel production capacities of these two companies are 29 MGPY and 14 MGPY respectively.

**Table S5.** Summary of water-stressed states from literature

|  |  |  |
| --- | --- | --- |
| Studies | Criteria | Water stressed areas |
| EPRI report22 | Water Supply Sustainability Index | AL, AZ, CA, FL, GA, ID, LA, NM, NV, TX, WA |
| Hurd et al.23  | Level of development, natural variability, dryness ratio, groundwater depletion, industrial water use flexibility and institutional flexibility | AZ, CA, CO, KS, NM, NV, TX, UT |
| Scown et al.24  | Palmer Drought Index | Southwestern US |
| Yang25 | Available precipitation | AZ, CA, CO, FL, GA, NV |

**Table S6.** Key assumptions and parameters of the studies

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | O’Connor8 | King and Webber5 | Harto et al.7  | Mulder et al.10  | This study |
| Parameters and Assumptions |
| Irrigation water loss % | 100% | 79.7% | 100% | 100% | 100% |
| % soybean irrigated | 8.2% | either 100% or 0% | 4% | NA | Overall:8.2% |
| Energy-water in irrigation | No | 0.158 gal/gal | No | No | No |
| Fertilizer water use | No | No | 11 gal/gal | No | No |
| Water intensity at different stages of the biodiesel process  |
| Normalized irrigation consumption (N*1*)  | 79 gal/gal | 200 gal/gal | 119.5 gal/gal | 716.35 gal/gal | 79 gal/gal |
| Normalized consumption during soybean crushing & processing(N*2*) | NA | 0.009 gal/gal | No | No | 0.17 gal/gal |
| Soybean oil-to-biodiesel (N*3*) | NA | 0.158 gal/gal | 0.5gal/gal | 3.63gal/gal | 0.31 gal/gal |
| N*tot*(gal/gal) | 79 | 200.32 | 131 | 719.98 | 79.48 |

**Figure S1.** Irrigation water use at state level\* (W*1*, million gallons per year)

\* 35 out of 50 states have data

**Figure S2.** The irrigation water intensity by state (N*1*, gallon water per gallon biodiesel)

**Appendix S-1: Sample calculation for irrigation water consumption (W*1OH*) and normalized water intensity (N*1OH*) for Ohio**

***Irrigation water consumption for Ohio (W1OH)***

An example of calculation procedures for W*1* and N*1* for Ohio is provided below. Following the same principle, results can be calculated for the state-level irrigation water consumption for soybean growth by using state-specific data from USDA reports.9,14 According to Table S1**, the total irrigated area for soybean through primary water distribution methods is 1,056 acres in Ohio and the average acre-feet applied per acre is 3.2. Therefore, the total irrigation water for soybean in 2007 is:**

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Since one acre-foot equals 325,851 gallons:

 

Mass-based allocation:

According to the assumptions above, 19.5% ($F\_{soy}$) of soybean was oil, about 17% ($F\_{use}$) of the soybean oil in 2007 was used for biodiesel production4and 89% ($F\_{BioD}$) oil was eventually converted into biodiesel.13

So for the calculation of W*1*:



***Normalized irrigation water intensity for Ohio (N1OH)***

Assume one bushel soybean weighs about 60 pounds and the density of soybean biodiesel is 7.4 lb/gallon.

Since total harvested soybeans in bushel are 191,559,567, the normalized irrigation water consumption per bushel of soybean is:

 

So, the allocated water consumption for biodiesel from one bushel is:



Finally, the irrigation water consumption based on every single gallon of biodiesel is:

 

***Allocation factor for soybean growth stage***

$F\_{1}=F\_{soy}×F\_{use}×F\_{BioD}=19.5\%×17\%×89\%=0.03$

**Appendix S-2: Calculation of normalized water consumption (N*2*) and sample calculation for water consumption in soybean crushing and processing stage (W*2OH*) for Ohio**

***Normalized water consumption (N2) in soybean crushing and processing stage***

**According to the life cycle report by United Soybean Board,13 the water consumption during soybean processing and refining stage is: 1,167 and 65.9 kg/1,000 kg soybean oil for the two steps. Below is the conversion of water consumption occurred in this stage into normalized value based on one gallon of biodiesel.**

$$N\_{2}=\frac{\left(1,164+65.9\right)kg H\_{2}O}{1,000kg soybean oil}×\frac{1 m^{3}}{1,000 kg H\_{2}O }×\frac{900 kg soybean oil}{1 m^{3}}×F\_{use}×F\_{BioD}=0.17 gal/gal$$

As stated in the main text, N*2* is assumed to be uniformly applicable to all the states in this study.

***Water consumption during soybean crushing and processing for Ohio (W2OH)***

Also for the total water consumption in this stage (W*2*), the calculation is performed based on the same allocation principles. Below is the sample calculation for the State of Ohio.

From Table S1, the harvested soybean in 2007 is 191,559,567 bushels, which translates into $5.2×10^{9} kg$. By applying the consumption factor of 1,229.9 kg water /1000 kg oil (Table S2), the total water consumption before allocation is $6.4×10^{9} kg$. Following the same allocation procedure, the total water consumption during soybean crushing and processing stage for Ohio is 49.95 MMgy.

$$W\_{2OH}=191,559,567×\frac{60 lb soybean}{bushel}×F\_{soy}×\frac{0.454 kg}{lb}×\frac{1}{1,000}×\frac{\left(1,164+65.9\right)kg H\_{2}O}{1,000 kg soybean oil}×F\_{use}×F\_{BioD}×\frac{1 gal H\_{2}O}{3.78 kg H\_{2}O}×\frac{1 MMgy}{1,000,000 gal/yr}=49.95 MMgy$$

***Allocation factor for soybean crushing & processing stage***

$$F\_{2}=F\_{use}×F\_{BioD}=17\%×89\%=0.15$$

**Appendix S-3: Sample calculation for normalized (N*3*) and total water consumptions in biodiesel manufacturing stage (W*3OH*) for Ohio**

***Normalized water consumption (N3) in biodiesel manufacturing stage***

Three scenarios are proposed in this study to account for water consumption from different purification methods (water/day wash) and process operations (cooling tower makeup). Assuming water wash and dry wash both account for 50% of current biodiesel purification technology, an averaged value from the data representing different scenarios is obtained through following equation:

$$N\_{3}=\left\{\frac{1}{2}×\left[\left(Water Wash\_{upper}+Cooling Tower\_{water})+(Water Wash\_{lower}+Cooling Tower\_{water}\right)\right]+Cooling Tower\_{dry}\right\}×\frac{1}{2}=0.31 gal/ga$$

Where: $Water Wash\_{upper}$ and $Water Wash\_{lower}$ are the washing water consumptions (gal/gal) from upper and lower scenarios; $Cooling Tower\_{water} $and $Cooling Tower\_{dry}$ are the volumes of cooling tower makeup water (gal/gal) for water wash and dry wash scenarios.

***Total water consumption (W3OH) in biodiesel manufacturing stage for Ohio***

W*3* is calculated by following equation:



For a specific state, such as Ohio, the product of N*3* (0.31) and total biodiesel plant capacity (132 MMgy) yield a W*3OH* of 40.92 MMgy.

**Appendix S-4: Summary of water stressed areas from literature**

A few studies have identified water stressed areas (at state level), and are briefly summarized here. The EPRI report22 projected water sustainability stress for US in 2025. In this study, the precipitation that was not lost due to evapotranspiration (ET) was quantified and used as an approximate measurement of available renewable water. The precipitation and potential evapotranspiration (PET) data was collected from 344 climate divisions to cover continental US and was averaged from 1934 to 2002. Based on 1995 data, significant total freshwater withdrawal occurred in the areas such as AR, CA, FL, ID, LA, MO, eastern TX, and eastern WA. The calculation of withdrawal as a percentage of available renewable water (surface water part) showed that in some regions the ratio was over 100%, which indicated that supplementary water sources (such as natural river or manmade flow structures) were often needed. This phenomenon was most notable in southwestern regions of US. In terms of groundwater, the ratio between groundwater withdrawal and available renewable water (groundwater part) indicated the degree of exploitation of this precious reservation of water. A percentage over 100%, in many cases, indicated the occurrence of unsustainable withdrawals; and those over 100% ratios were found mainly in parts of AZ, CA, FL, ID, KS, NE, and TX. From the data above, the authors described a few scenarios based on the increases in population and electricity generation to predict and compare the water demand in 2025. The results showed that the above-mentioned regions were susceptible to the constraints by increased water demands. In addition to limitation by quantity of water, the authors also incorporated several regulatory constraints to develop a Water Supply Sustainability Index to evaluate the water supply constraints in the US based on the projection. Six criteria were included, which were: (1) extent of available renewable water development. The water use was not supposed to exceed 25% of the total available renewable water; (2) sustainable groundwater use. The ground water withdrawal was not expected to exceed 50% of the total available renewable water (groundwater part); (3) environmental regulatory constraints. No more than two endangered aquatic species were identified in the specific region where water use occurred; (4) susceptibility to drought. The region was considered to be susceptible to drought if its summer deficit during low precipitation years was greater than 10 inches; (5) Growth of water use. If the “business as usual” water use requirements to 2025 increased current freshwater withdrawal by more than 20%, the region triggered this sustainability concern; (6) Growth in demand for stored water. If the summer deficit increased more than one inch over 1995-2025, this criterion was triggered. Based on this index and the county-level data, if a county meets any two of these criteria, it is defined as “somewhat susceptible” to an unsustainable water supply practice. If three criteria are met, the county is “moderately susceptible”; and if four or more criteria are met, the county is considered as “highly susceptible”. Once again, according to the results, the susceptible areas were mainly located in the southwestern part of the US such as AZ, CA, NM and NV. Other susceptible regions were AL, FL, GA, ID, LA, TX and WA. Hurd et al.23 developed a matrix of indicators for assessing the vulnerability of water supply, distribution and consumptive use for 204 watersheds in the US. The indicators included: level of development, natural variability, dryness ratio, groundwater depletion, industrial water use flexibility and institutional flexibility. For in-stream use, water quality and ecosystem support, the authors also proposed an array of indicators to evaluate the changes in flood risk, navigation, ecosystem thermal sensitivity, dissolved oxygen, low flow sensitivity and species at risk. The detailed definition and calculation principles of these indicators can be found in the paper and hence are not elaborated here. From their study, it can be found that western US, specifically AZ, CA, CO, KS, NM, NV, TX, and UT, are vulnerable to water stress. Scown et al.24 studied both water withdrawal and consumption for biofuels. In their study, “drought-prone” areas (for surface water) were defined based on the Palmer Drought Index.S1 The Palmer Drought Index measures the long-term drought patterns, their duration and intensity, in a specific region. The county-level data for drought occurrence was collected by NOAA and the calculated index was used for mapping the US drought conditions. There are five categories reflecting the different severeness of drought, which are: “Abnormally Dry (D0)”, “Moderate Drought (D1)”, “Severe Drought (D2)”, “Extreme Drought (D3)” and “Exceptional Drought (D4)”. In Scown et al.,24 the areas with D2 or worse for more than 10% of the time in its last 100 years were selected as drought-prone areas (for surface water). For groundwater, 27 states were identified as susceptible to either significant decline in aquifer levels, subsidence or both. Accordingly, the maps plotted by the authors for drought-prone areas and groundwater impacts showed that southwestern US was more vulnerable to both of the two water constraints. Yang performed the projection of precipitation variability for contiguous US by using historical precipitation data from 1207 climatic stations. The results indicated that States of Arizona, California, Colorado, Florida, Georgia, and Nevada were susceptible to the potential of decreased precipitation in the future.25

**Appendix S-5: The Geographical Designation of 9 US Regions**

For regional analysis, the soybean irrigation water consumption (W*1*), biodiesel manufacturing water consumption (W*3*) and total water consumption (W*tot*) are all grouped for the region from each individual state. In this study, the 9 regions directly come from the US Census Bureau’s definition, which is also used by other authors in their study.21 The states within each region are listed below:

1. New England: Maine, New Hampshire, Vermont, Massachusetts, Connecticut, Rhode Island
2. Middle Atlantic: New York, New Jersey, Pennsylvania
3. East North Central: Ohio, Michigan, Indiana, Illinois, Wisconsin
4. West North Central: Missouri, Iowa, Minnesota, Kansas, Nebraska, South Dakota, North Dakota
5. South Atlantic: Maryland, Delaware, District of Columbia, Virginia, West Virginia, North Carolina, South Carolina, Georgia, Florida
6. East South Central: Kentucky, Tennessee, Alabama, Mississippi
7. West South Central: Arkansas, Louisiana, Oklahoma, Texas
8. Mountain: Montana, Wyoming, Colorado, New Mexico, Arizona, Utah, Nevada, Idaho
9. Pacific: Washington, Oregon, California

**Appendix S-6: Converting Literature Results (N*1*, N*2*, N*3*) into “Gal/Gal” form**

**N*1***

**O’Connor8:**

Irrigated area: 7,044,546 acre with 0.7 acre-feet/acre🡪total irrigation water (W*tot,2008*)=1,606,830 MG (2008 Farm and Ranch)

Total bushel yield (H*tot,2007*): 2,582,423,697 bushels (2007 Census of Agriculture)

(1) Before allocation: 1,606,830 MG total irrigation water /2,582,423,697 total bushels= 622 gallons irrigation water per bushel

(2) Allocation between soy oil and meal: 20% oil ($F\_{soy}$), 80% meal

(3) Further allocation between soy biodiesel ($F\_{BioD}=$89% of the soy oil), glycerin and meal: 17.8%, 2.2%, and 80%

**Allocation Equation:** $N\_{1}=\frac{\frac{W\_{tot,2008}}{H\_{tot,2007}}×F\_{soy}×F\_{BioD}}{V\_{BioD}}=\frac{622x20\%x89\%}{1.4}=79 gal/gal$

**Harto et al.7:**

(Below are cited from the supporting material of the article)

(1) Crop irrigation water: a national average of 6200 gallons H2O/bushel.

(2) One bushel of soy is needed to produce one gallon of biodiesel
(3) Average yield: 43.6 bushels soy/acre

(4) Percent of soybean production: 37% (Low), 49% (Mid), 14% (High) in low, mid and high cost farms.

Soybean acreage irrigated: 0% (Low), 3% (Mid), 18% (High) in low, mid and high cost farms

So average irrigation %: 0.37 \* 0 + 0.49 \* 0.03 + 0.14 \* 0.18 = 0.04, or 4%

(5) Average irrigation on irrigated soy farms: 0.8 acre-ft🡪 a national average of (0.8 acre-ft) \* 0.04 = 0.032 acre-ft= 10,427 gallon H2O/acre (with 4% irrigation ratio).

So before allocation: (10,427 gal H2O/acre) / (43.6 bushels/acre) / (1 gal biodiesel/bushel) = 239 gal H2O/gal biodiesel

**With a 0.5 overall allocation factor, the N*1* = 119.5 gal/gal**

**King and Webber5:**

(Below are cited from the supporting material of the article)

(1) One bushel of soybean generate 10.7 gallons of biodiesel

(2) Irrigation water consumed or lost in conveyance =79.7%

Average Irrigation (U.S.):

(3) Average amount of water used on irrigated soybean (ac-ft/acre/yr) = 0.8

(4) U.S. soybean yield of irrigated farms in 2002 (bushels/acre) = 48

So, before allocation, average gallons of irrigation water consumed per gallon of biodiesel:

 (0.8 ac-ft H2O/acre/yr)\*(79.7%)\*(325851.4 gal/ac-ft)\*(1 yr/crop)/[(48 bushels soy/acre)(1 gal biodiesel/1 gal refined soy oil)(10.7 gal refined soy oil/1 bushel soy)]

**=** 400 gal H2O/gal biodiesel

**After allocation with overall factor of 0.5, the average N1=200 gal/gal**

**Mulder et al.10:**

(1) Water usage for soybean irrigation =76.82 L/MJ

Allocation factor: $0.344×0.821=0.282$

After allocation = 21.70 L/MJ

The energy content of biodiesel=118,296 Btu/gal=124.8 MJ/gal

Convert water consumption into: 21.70 (L/MJ)/3.78 (L/gal)=5.74 gal/MJ

1 gal of biodiesel possess 124.8 MJ energy

**So after allocation, the irrigation water consumption is: 716.35 gal/gal**

**N*2***

**O’Connor8:**

**0**

**Harto et al.7:**

**0**

**King and Webber5:**

(Below are cited from the supporting material of the article)

(1) Water consumed for soybean crushing processes (kg/metric ton oil produced): 19.35

(2) Soybean oil density (lb/gal): 7.7

So before allocation, water consumed for soybean crushing processes (gal water/gal oil):

= (19.35 kg/metric tonne soy oil)\*(1 gal soy oil/gal biodiesel)\*(7.7 lb/gal soy oil)\*(4.448

N/lb)\*(264.17 gal/m3)/[(9.81 m/s2)\*(1000 kg/tonne)\*(997 kg/m3 H2O)]

= 0.018 gal H2O/gal biodiesel

**After allocation with an overall factor of 0.5, N2=0.009 gal/gal**

**Mulder et al.10:**

**0**

**N*3***

**O’Connor8:**

**0**

**Harto et al.7:**

Biodiesel fuel production was taken directly from reference: 1 gal/gal

So after allocation with an overall factor of 0.5, N*3*=0.5 gal/gal

**King and Webber**

(1) Water consumption during biodiesel manufacturing: 356 (kg/metric ton biodiesel)

Water consumed for converting soy oil to biodiesel (gal water/gal biodiesel):

= (356 kg/metric tonne biodiesel)\*(7.36 lb/gal biodiesel)\*(4.448 N/lb)\*(264.17

gal/m3)/[(9.81 m/s2)\*(1000 kg/tonne)\*(997 kg/m3 H2O)]

= 0.315 gal H2O/gal biodiesel

**After allocation (0.5), N3= 0.158 gal/gal**

**Mulder et al.10:**

(1) Water usage for biodiesel manufacturing stage = 0.14 (L/MJ)

After allocation factor = 0.821

So after allocation, the irrigation water consumption is: 3.63 gal/gal

**N*tot***

**O’Connor8:** **79 gal/gal**

**Harto et al.7: 200.32 gal/gal**

**King and Webber5: 131 gal/gal**

**Mulder et al.10: 719.98 gal/gal**

**References**

S1. *Objective Long‐Term Drought Indicator Blend Percentiles*. National Oceanic and

Atmospheric Administration: Washington, DC, 2010;

<http://www.cpc.ncep.noaa.gov/products/predictions/tools/edb/lbfinal.gif> (accessed on March 2013)