Water Consumption Footprint and Land Requirements of Large-Scale Alternative Diesel and Jet Fuel Production*

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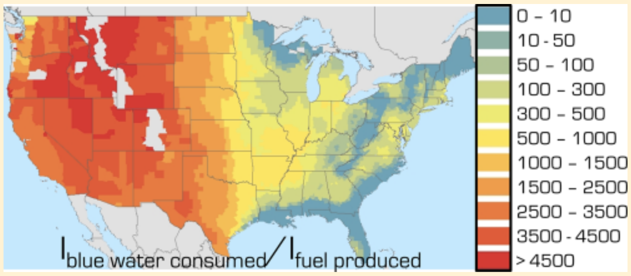
Ⓢ *Supporting Information*



ABSTRACT: Middle distillate (MD) transportation fuels, including diesel and jet fuel, make up almost 30% of liquid fuel consumption in the United States. Alternative drop-in MD and biodiesel could potentially reduce dependence on crude oil and the greenhouse gas intensity of transportation. However, the water and land resource requirements of these novel fuel production technologies must be better understood. This analysis quantifies the lifecycle green and blue water consumption footprints of producing: MD from conventional crude oil; Fischer–Tropsch MD from natural gas and coal; fermentation and advanced fermentation MD from biomass; and hydroprocessed esters and fatty acids MD and biodiesel from oilseed crops, throughout the contiguous United States. We find that FT MD and alternative MD derived from rainfed biomass have lifecycle blue water consumption footprints of 1.6 to 20.1 L_{water}/L_{MD}, comparable to conventional MD, which ranges between 4.1 and 7.4 L_{water}/L_{MD}. Alternative MD derived from irrigated biomass has a lifecycle blue water consumption footprint potentially several orders of magnitude larger, between 2.7 and 22 600 L_{water}/L_{MD}. Alternative MD derived from biomass has a lifecycle green water consumption footprint between 1.1 and 19 200 L_{water}/L_{MD}. Results are disaggregated to characterize the relationship between geo-spatial location and lifecycle water consumption footprint. We also quantify the trade-offs between blue water consumption footprint and areal MD productivity, which ranges from 490 to 4200 L_{MD}/ha, under assumptions of rainfed and irrigated biomass cultivation. Finally, we show that if biomass cultivation for alternative MD is irrigated, the ratio of the increase in areal MD productivity to the increase in blue water consumption footprint is a function of geo-spatial location and feedstock-to-fuel production pathway.

■ INTRODUCTION

Efforts to reduce dependence on crude oil and to mitigate the impact of transportation on the environment have motivated research on alternative fuels in the United States (U.S.). Alternative drop-in middle distillate (MD) transportation fuels, including diesel and jet fuels that are chemically similar to conventional petroleum-derived MD, and biodiesel, are of particular interest because MD fuels make up almost 30% of liquid fuel consumption in the U.S.[1] Unlike ethanol, alternative drop-in diesel and biodiesel are compatible with existing diesel trucks, automobiles, railroad locomotives and agricultural machinery, and alternative drop-in jet fuel is compatible with turbojet and turboprop aircraft engines.[2,3] (We note that biodiesel is not usable in aviation, and is not compatible with existing pipeline infrastructure due to contamination concerns.)

Alternative MD technologies may hold promise in terms of reduced lifecycle greenhouse gas (GHG) and air quality-degrading emissions compared to conventional MD.[4−6] However, while the overall environmental impacts of biofuel technologies have been studied,[7−14] the water and land resource requirements of novel alternative MD production technologies have not been quantified. Alternative MD production technologies are distinct from other biofuels in terms of the unit processes and efficiencies of feedstock-to-fuel conversion. Both of these factors are determinants of alternative MD fuels' environmental impact. Furthermore, despite uncertainty about their environmental impacts, production of alternative MD fuels is expected to grow: the International Air Transport Association (IATA) has a goal of 10% alternative fuel use for aviation by 2017,[15] and the U.S. Federal Aviation Administration (FAA) has a goal of one billion gallons of alternative fuel consumption by 2018.[16] Additionally, the U.S. Renewable Fuels Standard 2 (RFS2) mandates 36 billion gallons of alternative fuel production by 2022, 21 billion gallons of which could be alternative MD or biodiesel.[17]

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Water used within the MD production lifecycle comes from precipitation, soil moisture, surface and underground sources. Fresh water from precipitation and soil moisture is categorized as green water, fresh water from surface and underground sources is categorized as blue water, and polluted water is categorized as gray water.[18] Water that exits a defined system boundary via direct consumption or evapotranspiration, and is no longer available for use, is considered consumed and may be either green or blue water.[19] This analysis encompasses both green and blue water consumed during the MD lifecycle. We perform additional analysis with respect to blue water consumption because it has a relatively higher opportunity cost than green water,[20] and alternative MD production may compete with other anthropogenic uses for blue water resources.[13,21] We note that there is gray water associated with all of the fuel pathways investigated, but that gray water is beyond the scope of our analysis.

The MD production pathways considered in this analysis include

- Conventional MD production
- Fischer−Tropsch (FT) MD from natural gas and coal
- Fermentation and advanced fermentation (AF) MD from sugar cane, corn, and switchgrass
- Hydroprocessed esters and fatty acids (HEFA) MD from soybean, rapeseed and jatropha
- Biodiesel from soybean, rapeseed and jatropha.

Conventional MD was included in this study for the purposes of comparison, and the alternative MD pathways were selected for feasibility of large-scale production in the near-term: FT and HEFA fuels have already been certified under ASTM D4054; AF (specifically alcohol-to-jet fuel) is expected to be among the next to be certified;[22] and in 2011, almost 1 billion gallons of biodiesel were consumed for ground transportation in the U.S.[23]

Although alternative MD and ethanol production pathways use similar biomass feedstocks, MD production technologies are distinct in terms of the unit processes employed for fuel production, and the mass efficiency of feedstock-to-fuel conversion. Therefore, the water footprint of alternative MD production will vary significantly from that of other biofuels. An analysis of the lifecycle water footprint of MD fuel production is absent from the literature because previous studies have focused exclusively on ethanol and biodiesel. Additionally, previous work has generally presented results as a range to capture variability and uncertainty in the input parameters.[10,11,13,24] Studies that have geo-spatially disaggregated results have done so at a coarse resolution,[7] or only at the regional scale.[25] This analysis is the first to calculate the water consumption footprint of alternative MD production pathways, geo-spatially disaggregated for the contiguous US at a county-level resolution, and to quantify the trade-offs between the water and land requirements of alternative fuel production.

■ MATERIALS AND METHODS

The green and blue water consumption footprint of each feedstock-to-fuel pathway is calculated on a lifecycle basis, taking into account the consumption of green water during biomass cultivation, and of blue water in each lifecycle step. In order to understand the drivers of variability in these results, the AF and HEFA pathway results are geo-spatially disaggregated at a county resolution for the contiguous U.S. Biodiesel results are not geo-spatially disaggregated because they agree with the HEFA results within ±6% for each county due to similar feedstock-to-fuel process water requirements and conversion efficiencies. Marginal resource requirement curves are constructed for the AF and HEFA pathways, ranked by the blue water consumption footprints and land requirements of MD production, and we test three different assumptions to quantify the trade-offs between blue water consumption and land use requirements for 10 billion liters per year of MD production from each pathway. Ten billion liters is used for comparison because, given the constraining assumptions, it is a volume of fuel that could be produced by each AF and HEFA MD pathway. Finally, the areal productivity benefit of irrigation is calculated on a county basis to quantify which regions of the contiguous U.S. will realize the greatest benefit from biomass irrigation for AF and HEFA MD production.

Lifecycle Methodology. In order to compare water consumption across pathways, we adopt a lifecycle methodology consistent with the principles described in Allen et al.,[26] and employed for previous sustainability assessments of alternative MD fuel production.[6] This analysis includes, when applicable, biomass cultivation, recovery and transportation; feedstock extraction, recovery and transportation; feedstock-to-fuel conversion; and transportation and distribution of MD. Water vapor released to the atmosphere during MD combustion is beyond the system boundary.

For green water we assume that the only lifecycle step of interest is the cultivation of biomass for alternative MD production, during which precipitation and soil moisture is consumed via evapotranspiration.

For blue water, two types of consumption are accounted for within the system boundary: (i) direct blue water consumption, which exits the system boundary during MD production; and (ii) indirect blue water consumption due to the blue water consumption footprints of the material and energy inputs to MD production. Blue water is consumed directly during biomass feedstock cultivation if surface or groundwater is applied for irrigation. We assume that no significant direct blue water consumption is associated with the transportation of the biomass and fossil fuel feedstocks, or fuel products, of any pathway, consistent with previous studies on the water footprint of transportation fuels.[11] For indirect blue water consumption, the quantities of primary energy carriers associated with transportation, such as coal, natural gas, and refinery products, were obtained from the default assumptions in GREET 2011.[27] The blue water consumption of: coal is taken from Gleick[19]; natural gas is calculated using a weighted average of conventional and shale gas extraction methods from Gleick[19] and King & Webber[10]; and crude oil products is calculated using the iterative procedure described in the Supporting Information (SI).

The material and energy outputs of each MD production pathway include products (e.g., diesel, jet fuel, and biodiesel), and coproducts (e.g., animal feed, electricity and non-MD fuels) or wastes. Water consumption is allocated among nonfuel coproducts according to market allocation: at the point where the fuel-destined product stream is physically separated from the coproduct streams, water consumption is allocated among the process streams in proportion to their relative market values.[28] The remaining water consumption is allocated among all fuel products according to their relative energy contents,[28] and results are reported in terms of liters of water consumed (either green or blue) per liter of MD produced [L_{water}/L_{MD}]. These allocation methods are consistent with previous sustainability assessments of alternative MD production pathways.[6]

Results are reported for each pathway in terms of green water and blue water, under assumptions of rainfed and irrigated biomass cultivation, where applicable. A range of low, mid, and high results does not represent uncertainty, but rather variability in the assumed locations of biomass cultivation, fossil fuel extraction methods, feedstock-to-fuel conversion efficiencies, and process water requirements. The mid value is calculated from the combination of assumptions most representative of the technology on the basis of engineering assumptions and empirical data. These assumptions are detailed in the SI.

Conventional MD. The conventional MD pathway lifecycle includes crude oil recovery, crude oil transportation, refining of crude oil to MD, and MD transportation and distribution.

The process of crude oil recovery consumes blue water as water or steam is injected into geological formations to maintain reservoir pressure.[24,29] The blue water consumption of crude oil extraction varies mainly according to the produced water reinjection technologies employed in each Petroleum Administration Defense District (PADD). An average of 3.3 L of blue water consumption per liter of crude oil produced is estimated for the U.S.[24]

Refining separates crude oil into its constituent hydrocarbons, removes impurities, and increases marketable fuel yields. The process consists of fractional distillation, mercaptan oxidation or hydrodesulphurization, and hydrotreatment. This analysis assumes a product slate that is 22.9% MD fuels,[30] and that 1.5 L of blue water is consumed per liter of crude oil refined, 96% of which is consumed for steam and cooling operations.[24] Variability in the results for the conventional MD pathway is due to assumptions regarding the blue water consumption of crude oil recovery and extraction in the different PADDs from Wu et al.[24] We expand on the blue water consumption footprint of MD reported by Wu et al.[24] by including indirect blue water consumption from transportation and material and energy inputs, and by allocating results among refinery fuel products.

FT MD from Natural Gas and Coal. The FT MD pathway lifecycle includes natural gas (NG) or coal feedstock recovery, feedstock transportation, feedstock-to-fuel conversion, and MD transportation and distribution. The blue water consumption of natural gas from conventional and shale deposits (produced using hydraulic fracturing) is assumed to be 0.109 and 0.134 L_{water}/MJ_{NG}, respectively.[19,10] Coal from open pit and underground coal mining operations, including washing to remove contaminants, is assumed to have blue water consumption intensities of 0.161 and 0.169 L_{water}/MJ_{coal}, respectively.[19]

The FT feedstock-to-fuel conversion process consists of two steps. During gasification or steam reforming, the feedstock is partially oxidized into synthesis gas (syngas) containing carbon monoxide and hydrogen, which is then purified to remove impurities such as sulfur. FT synthesis then takes place, which is a polymerization reaction of carbon monoxide in the presence of hydrogen and an iron- or cobalt-based catalyst.[6] For the purposes of this analysis, it is assumed that the 70% of the fuel product of the FT process is MD by energy.[31] Blue water is consumed for electricity production, cooling processes, the water−gas shift reaction, and steam reforming of natural gas to hydrogen. Variability in the results for the FT MD pathways is due to assumptions regarding the feedstock extraction process, lower heating value (LHV) conversion efficiency, and the direct process water use, from Bao et al.,[32] Matripragada,[33] and Stratton et al.[6]

AF MD Production from Sugar Cane, Corn and Switchgrass. The AF MD pathway lifecycle includes biomass cultivation and transportation, feedstock-to-fuel conversion, and MD transportation and distribution. The feedstocks considered for the AF MD pathway are sugar cane, corn, and switchgrass.

Once at the AF facility, three steps are required for conversion of the feedstock to MD: monomer sugar is extracted from the feedstock via pretreatment and hydrolysis; the sugar is metabolized by an engineered microorganism to produce a platform molecule; and the platform molecule is upgraded to drop-in fuel. The process parameters associated with feedstock-to-fuel conversion, such as electricity, natural gas, and fresh water makeup requirements; feedstock-to-fuel conversion efficiencies; and the quantity of coproducts produced, are calculated from the literature.[34−53] Variability in the results for the AF MD pathways is due to the choice of feedstock, feedstock-to-fuel conversion process parameters, and the assumed location of biomass and fuel production.

HEFA MD and Biodiesel from Soybean, Rapeseed, and Jatropha. The HEFA MD and biodiesel pathway lifecycles include biomass cultivation and transportation, vegetable oil extraction and transportation, vegetable oil to MD or biodiesel conversion, and fuel transportation and distribution. The feedstocks considered for the HEFA MD and biodiesel pathways are soybean, rapeseed and jatropha.

Vegetable oil is extracted from the biomass by pressing the oilseeds and introducing an organic solvent, such as hexane.[47] In the case of soybean and rapeseed, the meal separated from the oil has a high protein content with commercial value as an animal feed. In the case of jatropha, the husks, shells and meal from most varieties are toxic to humans, so it is assumed that the coproducts are combusted to produce electricity.[6] At a HEFA MD facility, the vegetable oil is hydrodeoxegenated and isomerized to drop-in fuel, approximately 91% of which is MD by energy content.[44] In the process used in this analysis, 89% of direct fresh water consumption is for boiler feedwater makeup due to steam generation and cooling losses.[44] Alternatively, at a biodiesel facility, the vegetable oil is transesterified to biodiesel.[47] Variability within the HEFA MD and biodiesel pathway results is due to the choice of feedstock; biomass growth, oil extraction and oil yield assumptions; and the assumed location of biomass and fuel production.

Global Agro-Ecological Zones (GAEZ) Model. For the pathways that use biomass feedstocks, the green and blue water consumption footprints of feedstock cultivation were taken from the GAEZ v3.0 model. GAEZ calculates geography and climate specific crop water balances to estimate evapotranspiration, crop water deficit during the growth cycle, and maximum attainable biomass yields. GAEZ also accounts for year-to-year average climatic and soil moisture variability and yield losses due to disease, water stress, soil workability, and early or late frosts. Evapotranspiration and biomass yields, under intermediate input conditions and for rainfed and irrigated conditions, were extracted from GAEZ for all six biomass feedstocks of interest, at a 5 arc-minute and 30 arc-second resolution. The data was used to calculate green water consumption, blue water irrigation requirements, and maximum attainable irrigated and rainfed yields. This was calculated for each county in the contiguous U.S. which GAEZ determines is suitable, given soil and climatic conditions, for cultivation of the crop of interest.[54]

■ RESULTS AND DISCUSSION

Results are reported as a range of low, mid, and high values for the lifecycle green and blue water consumption footprints of each MD production pathway. The results are geo-spatially disaggregated for the AF and HEFA pathways to quantify the effect of the assumed location of biomass feedstock cultivation and MD production on the results. The trade-offs between blue water consumption footprint and areal productivity are also quantified.

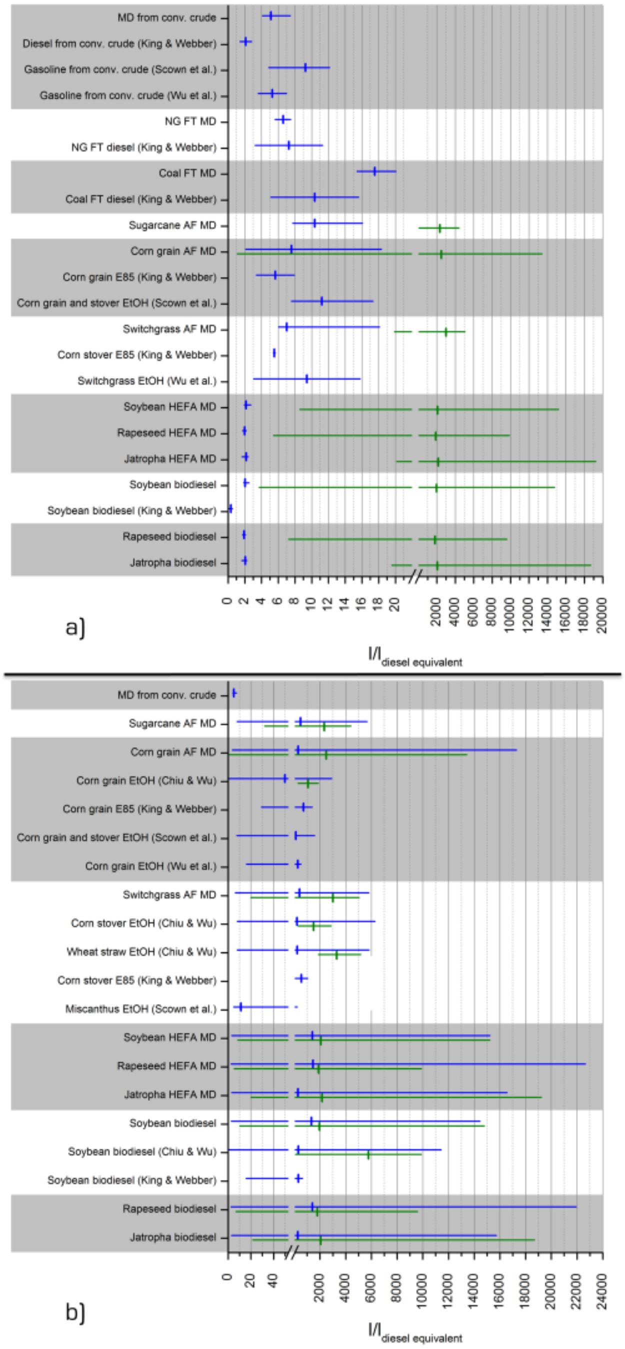

Figure 1. Lifecycle water consumption of MD production via (a) FT pathways and rainfed biomass cultivation, and (b) irrigated biomass cultivation. The conventional MD pathway results are shown in both instances for the purposes of comparison. Results shown are calculated by this analysis unless otherwise cited. Blue water results are shown in blue, and green water results are shown in green.

Results and Geo-Spatial Disaggregation. The results for all pathways studied in this analysis are shown in Figure 1, and are compared to the literature under assumptions of rainfed and irrigated biomass cultivation.[7,10,11,24] Because this is the first analysis to calculate the green and blue water consumption footprints of alternative MD production technologies, and previous studies have focused primarily on conventional petroleum fuels and ethanol, the results are compared to the literature on the basis of the energy equivalent of a liter of conventional diesel. The whiskers in Figure 1 indicate variability in the results: for example, the low and high results for the blue water consumption of the irrigated AF switchgrass pathway are 6.2 and 5800 L_{water}/L_{MD}, respectively. These correspond to the combinations of biomass feedstock cultivation, and feedstock-to-fuel conversion parameter assumptions that yield the lowest and highest results. Comparison with the literature shows that our results are congruent with the range of values previously reported for other fuels. For example, Figure 1 shows that the low, mid and high results for conventional MD (4.1, 5.1, and 7.4) lie in the midst of results calculated by King & Webber,[10] Scown et al.,[11] and Wu et al.[24]

Figure 1a shows that the blue water consumption footprint of rainfed biomass-derived and FT MD production ranges between 1.6 and 20.1 L_{water}/L_{MD}. With the possible exception of FT MD from coal, alternative MD production has a blue water consumption footprint comparable to MD from conventional crude under an assumption of rainfed biomass cultivation. In contrast, Figure 1b demonstrates that under an assumption of irrigated biomass cultivation, alternative MD pathways that use biomass feedstocks have blue water consumption footprints several orders of magnitude greater than MD from conventional crude. For example, rainfed soybean HEFA MD has a blue water consumption footprint of 2.1 L_{water}/L_{MD}, compared to conventional MD with 5.1 L_{water}/L_{MD} under mid assumptions. However, irrigated soybean HEFA MD has a blue water consumption footprint of 1407 L_{water}/L_{MD} under mid assumptions. The large blue water consumption footprints of the pathways in Figure 1b) are due to the water requirements of irrigation. For example, the biomass cultivation step accounts for 1405 L_{water}/L_{MD}, or 99.9%, of the total lifecycle blue water consumption footprint for soybean HEFA MD. The green water consumption footprint of biomass-derived alternative MD pathways ranges between 1.1 and 19 230 L_{water}/L_{MD}. It should be noted that conventional and FT MD fuels have no green water consumption footprint.

Figure 1 shows a range of values in order to capture variability in the assumptions related to irrigation requirements, feedstock-to-fuel process water requirements, and conversion efficiency. We further disaggregate the AF and HEFA pathway results to investigate the largest source of variability: the assumed location of biomass feedstock cultivation and MD production. Geo-spatial location determines the climate and soil conditions, water consumption, and areal productivity of biomass cultivation, and indirect blue water consumption footprint of electricity in each county. The green and blue water consumption of biomass cultivation is extracted from the GAEZ model,[54] and the indirect blue water consumption footprint of electricity, at a county-level resolution, is from

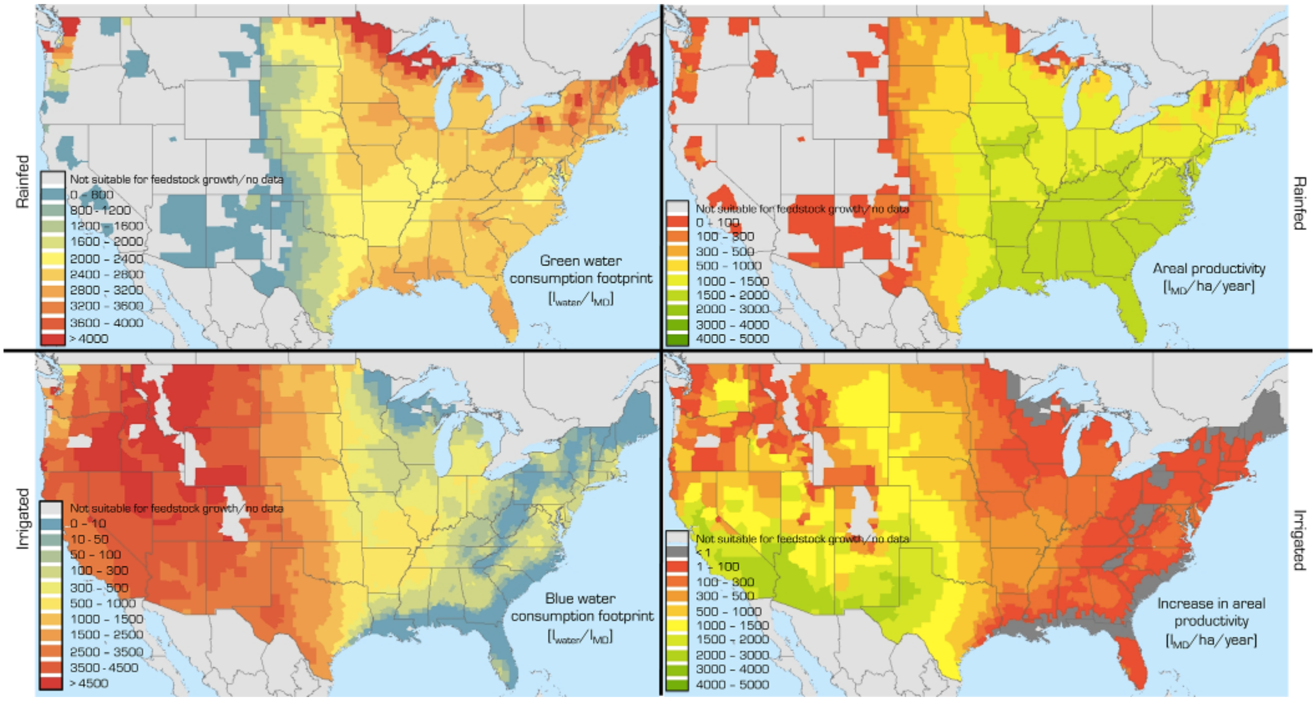

Figure 2. Lifecycle water consumption footprint and areal productivity of rainfed and irrigated corn AF MD production.

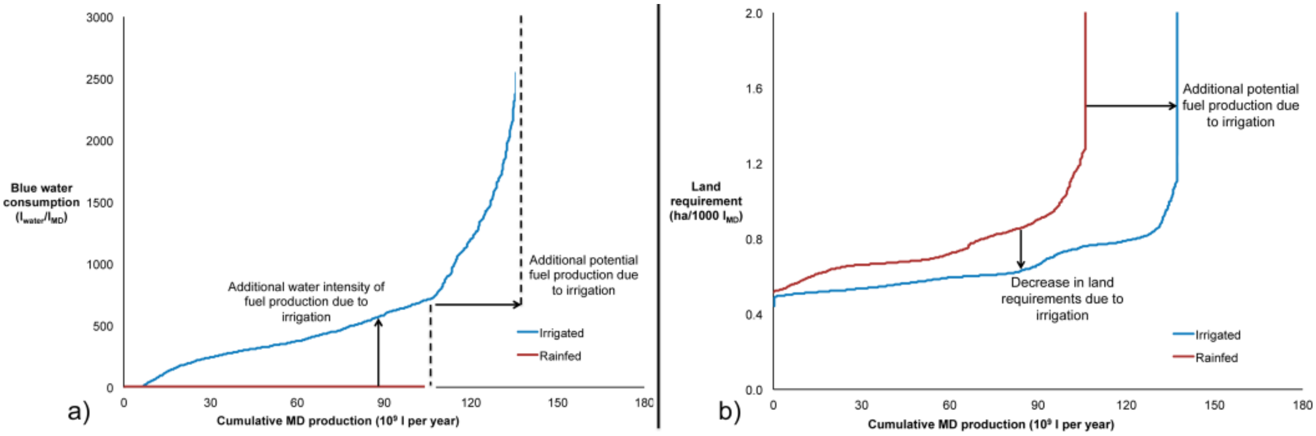

Figure 3. (a) Marginal blue water consumption of rainfed and irrigated corn AF MD production, counties ranked to minimize water requirements. (b) Land requirements of rainfed and irrigated corn AF MD production, counties ranked to minimize land requirements.

Strzepek et al.[55] The green and blue water consumption requirements of feedstock irrigation are associated to counties, and lifecycle results are calculated for each pathway under the assumptions of rainfed and irrigated maximum attainable biomass cultivation. The areal productivity of MD production is calculated using maximum attainable biomass feedstock yield data from GAEZ, under assumptions of intermediate cultivation inputs. The feedstock-to-fuel process water requirements and conversion efficiencies are held constant at the mid assumption parameters described in the SI. An example of the results for the corn AF MD pathway is shown in Figure 2. The left side of Figure 2 shows the green and blue water consumption footprints under an assumption of rainfed and irrigated biomass cultivation, respectively. The blue water consumption footprint of MD production is higher under an assumption of irrigated biomass, and increases as irrigated biomass cultivation occurs in drier climates in the western states. Conversely, green water consumption footprint decreases as biomass cultivation occurs in drier climates. For example, the green and blue water consumption footprints of irrigated corn AF MD production are 2450 $L_{green\ water}/L_{MD}$ and 329 $L_{blue\ water}/L_{MD}$ in Robertson, TN, and 1340 $L_{green\ water}/L_{MD}$ and 1960 L_{water}/L_{MD} in Dewey, OK, respectively. This pattern demonstrates an inverse relationship between green and blue water consumption footprints. The increase in areal productivity of corn AF MD, due to irrigated biomass cultivation, is shown in the bottom right of Figure 2. Under an assumption of rainfed corn AF MD production areal productivity is 1620 L_{MD}/ha/year, and increases to 1810 L_{MD}/ha/year under an assumption of irrigated corn AF MD production in Robertson, TN. Additional results are reported in the SI.

In order to quantify the trade-offs between blue water consumption footprint and areal productivity of large-scale alternative MD production, marginal resource requirement

Table 1. Lifecycle Blue Water Consumption Footprint and Areal Productivity, Averaged Over 10 Billion Liters of Cumulative MD Production from Each Pathway, Under Three Different Assumptions

metric	pathway	rainfed biomass cultivation	irrigated biomass cultivation, water use minimized	irrigated biomass cultivation, areal prod. maximized
average water footprint l_{water}/l_{MD}	sugar cane AF	10.4	220	689
	corn AF	5.2	16.6	1250
	switchgrass AF	4.7	129	1440
	soybean HEFA	2.1	50.0	1170
	rapeseed HEFA	1.8	2.0	811
	jatropha HEFA	2.1	20.9	455
average areal productivity $1000\ l_{MD}/ha$	sugar cane AF	3.8	3.4	4.2
	corn AF	1.2	1.7	2.0
	switchgrass AF	2.2	2.5	3.5
	soybean HEFA	0.49	0.71	0.82
	rapeseed HEFA	0.99	1.1	1.3
	jatropha HEFA	2.1	2.2	2.4

curves are constructed for the AF and HEFA pathways. We rank the counties in the contiguous U.S. by the blue water consumption footprint and land requirements of MD production, and plot against the cumulative MD production capacity of that county for each AF and HEFA production pathway. The MD production capacity of each county is calculated on the basis of agro-climatically maximum attainable areal biomass productivity from GAEZ, and the calculated feedstock-to-fuel conversion efficiency. Each county's MD production capacity is constrained by available harvested cropland from the 2007 USDA Census of Agriculture,[56] and available fresh water resources, without inducing a water stress index above 0.4, from the USDA Forest Service Water Supply Stress Index (WaSSI).[57] These constraints are applied only for the analyses shown in Figures 3 and 5, and Table 1, because they require an estimate of potential MD fuel production volumes in each county. Examples of the marginal water and land resource requirement curves for the corn AF MD pathway are shown in Figure 3. Additional results are reported in the SI.

The marginal resource requirement curves are stacked to minimize either blue water consumption or land footprint, and they illustrate the trade-offs between blue water consumption and land use. In order to quantify these trade-offs, the blue water consumption footprint and areal productivity of the AF and HEFA pathways are averaged over 10 billion liters of cumulative MD production under three different assumptions: rainfed cultivation; irrigated cultivation with blue water consumption footprint minimized; and irrigated cultivation with areal productivity maximized. The results are shown in Table 1. Blue water consumption footprint and areal productivity range from 1.8 to 1440 L_{water}/L_{MD} and 490 to 4200 L_{MD}/ha/year, respectively.

Areal Productivity Benefit of Irrigation. In order to relate the blue water footprint and areal productivity characteristics quantified in this analysis, we calculate the ratio of increased areal productivity to increased blue water consumption footprint, on a county basis, for the AF and HEFA pathways. This value is defined as $M = \Delta Y/\Delta W$, where M is the areal productivity benefit of irrigation (1000 L_{MD}/ha per L_{water}/L_{MD}), ΔY is the increase in maximum attainable areal fuel yield due to irrigated (versus rainfed) biomass cultivation (1000 L_{MD}/ha), and ΔW is the increase in blue water consumption footprint due to irrigated (versus rainfed) biomass cultivation (L_{water}/L_{MD}).

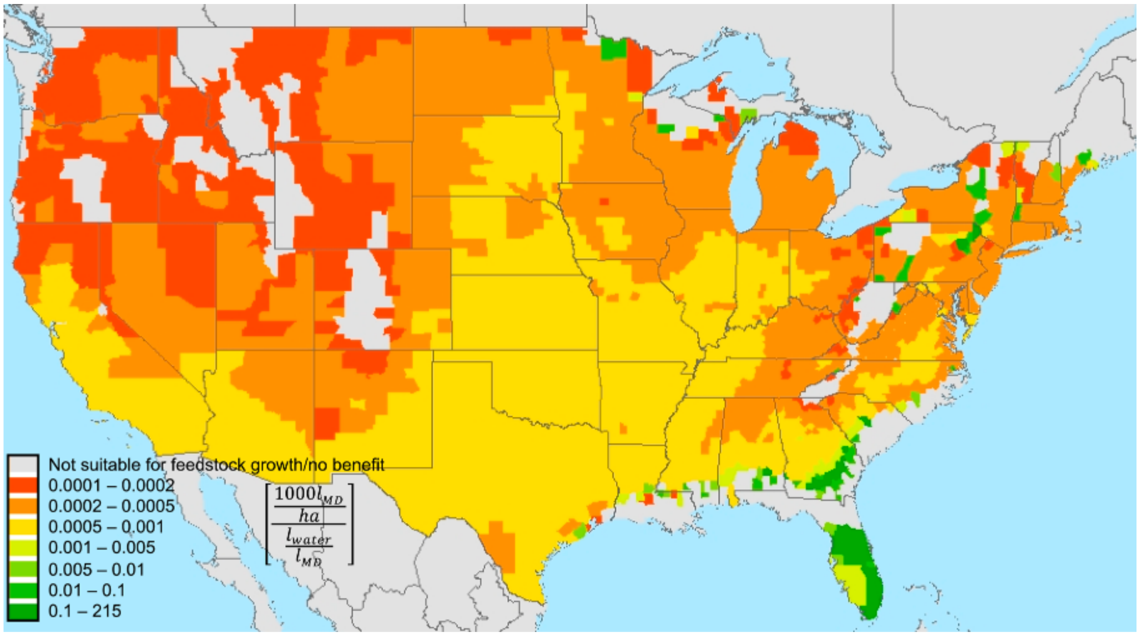

Figure 4. Areal productivity benefit of irrigation, M, for corn AF MD production.

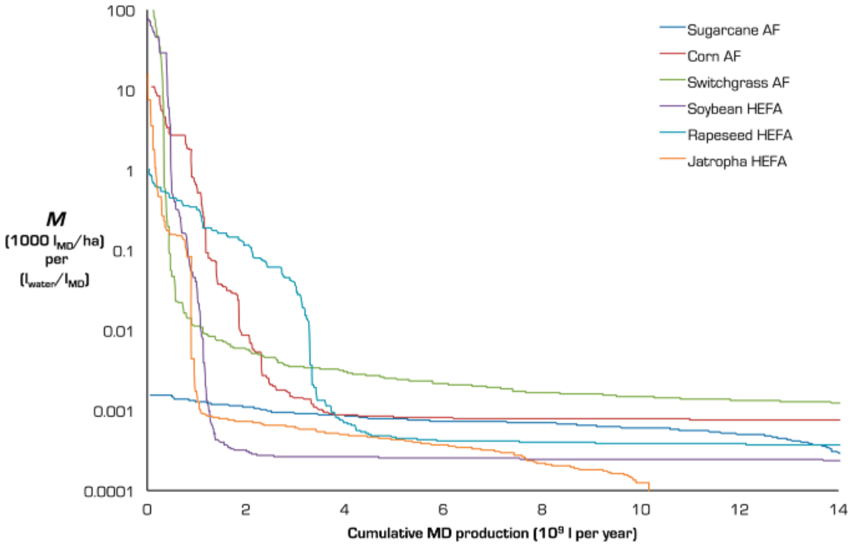

Figure 5. Areal productivity benefit of irrigation for alternative MD production.

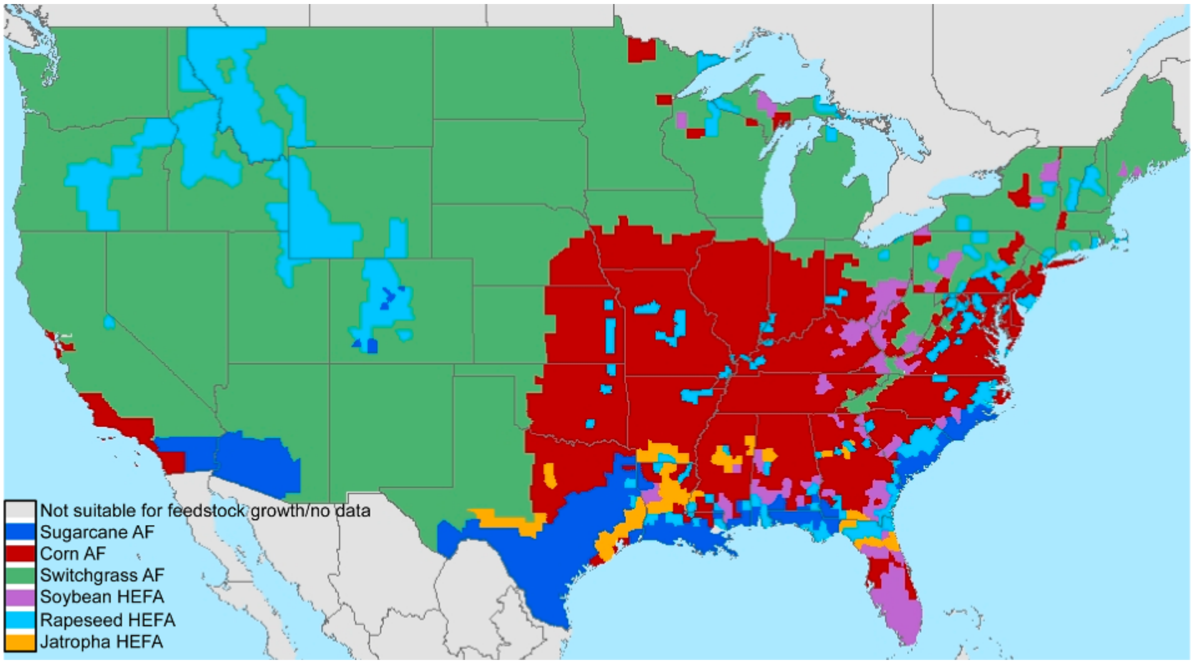

Figure 6. MD production pathway with the greatest areal productivity benefit from irrigation in each county.

The ratio M is calculated for each county in the contiguous U.S. that GAEZ determines is suitable for cultivation of the biomass feedstock of interest. A higher value of M indicates that the areal productivity to be gained from irrigation comes with a relatively small increase in blue water consumption footprint. Conversely, a low value of M indicates that there is little areal productivity improvement to be realized, or that it comes at the cost of a relatively large increase in blue water consumption footprint. An example of the result of this calculation for the corn AF MD pathway is shown in Figure 4.

In order to compare the potential for areal productivity benefits from irrigation between the AF and HEFA pathways, the results are ranked by the ratio M, and plotted against cumulative MD production. This is shown in Figure 5. This implies that at different scales of production, different feedstock-to-fuel pathways have distinct areal productivity benefits from irrigation.

Figure 6 shows which fuel pathway has the greatest value of M under an assumption of irrigated biomass cultivation for alternative MD production in each county in the contiguous U.S. Relative to the other pathways, corn AF enjoys the greatest areal productivity benefit in the Central and Southern Plains States and the Mississippi Valley regions; switchgrass AF in the Great Lakes and Northeast regions, and most of the western U.S.; rapeseed HEFA in the Rocky Mountain and Western States; and sugar cane AF enjoys the greatest benefit in the Gulf Coast regions of Texas and Louisiana, and southern California and New Mexico.

We note that the decision to irrigate in any particular location depends on a number of additional factors, such as: the impacts of irrigation practices on local water stress and water quality; agricultural profit-maximization; and, most importantly for this analysis, the local price and scarcity of water and land resources. Further research is required to understand these additional impacts of large-scale alternative MD fuel production.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Further information on: data extracted from GAEZ and the way in which irrigated biomass cultivation blue water consumption requirements were calculated; data sources and descriptions for calculation of the mass and energy flows associated with all MD feedstock-to-fuel production pathways; the assumptions used for low, mid and high cases; tabular results; and mapped results for all HEFA and AF pathways. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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■ REFERENCES

(1) Petroleum & Other Liquids; United States Energy Information Agency: Washington, DC, 2013; http://www.eia.gov/dnav/pet/pet_cons_wpsup_k_4.htm.

(2) Definitions of Petroleum Products and Other Terms; United States Energy Information Agency: Washington, DC, 2013; http://www.eia.gov/pub/oil_gas/petroleum/survey_forms/defntnp4.pdf.

(3) Hileman, J. I.; Wong, H. M.; Waitz, I. A.; Ortiz, D. S.; Bartis, J. T.; Weiss, M. A.; Donohoo, P. E. near-Term Feasibility of Alternative Jet Fuels; The RAND Corporation and the Massachusetts Institute of Technology: Cambridge, MA, 2009.

(4) Carter, N. A.; Stratton, R. W.; Bredehoeft, M. K.; Hileman, J. I. Energy and environmental viability of select alternative jet fuel pathways, 47th AIAA/ ASME/ SAE/ ASEE Joint Propulsion Conference & Exhibit, San Diego, CA, August 2011.

(5) Lobo, P.; Hagen, D. E.; Whitefield, P. D. Comparison of PM emissions from a commercial jet engine burning conventional, biomass, and Fischer−Tropsch fuels. Environ. Sci. Technol. **2011**, 45 (24), 10744−9, DOI: 10.1021/es201902e.

(6) Stratton, R. W.; Wong, H. M.; Hileman, J. I. Quantifying variability in life cycle greenhouse gas inventories of alternative middle distillate transportation fuels. Environ. Sci. Technol. **2011**, 45 (10), 4637−44, DOI: 10.1021/es102597f.

(7) Chiu, Y. W.; Wu, M. Assessing county-level water footprints of different cellulosic-biofuel feedstock pathways. Environ. Sci. Technol. **2012**, 46 (16), 9155−62, DOI: 10.1021/es3002162.

(8) Dominguez-Faus, R.; Powers, S. E.; Burken, J. G.; Alvarez, P. J. The water footprint of biofuels: A drink or drive issue? Environ. Sci. Technol. **2009**, 43 (9), 3005−3010, DOI: 10.1021/es802162x.

(9) Fargione, J. E.; Cooper, T. R.; Flaspohler, D. J.; Hill, J.; Lehman, C.; Tilman, D.; McCoy, T.; McLeod, S.; Nelson, E. J.; Oberhauser, K. S. Bioenergy and wildlife: Threats and opportunities for grassland conservation. BioScience **2009**, 59, 767−777, DOI: 10.1525/bio.2009.59.9.8.

(10) King, C. W.; Webber, M. E. Water intensity of transportation. Environ. Sci. Technol. **2008**, 42 (21), 7866−72, DOI: 0.1021/es800367m.

(11) Scown, C. D.; Horvath, A.; McKone, T. E. Water footprint of U.S. transportation fuels. Environ. Sci. Technol. **2011**, 45 (7), 2541−53, DOI: 10.1021/es102633h.

(12) Sheehan, J. J. Biofuels and the conundrum of sustainability. Curr. Opin Biotechnol. **2009**, 20 (3), 318−24, DOI: 10.1016/j.copbio.2009.05.010.

(13) Tidwell, V.; Sun, A.; Malczynski, L. Biofuel Impacts on Water; Sandia National Laboratories: Albuquerque, NM, 2011.

(14) Yang, H.; Zhou, Y.; Liu, J. Land and water requirements of biofuel and implications for food supply and the environment in China. Energy Policy **2009**, 37, 1876−1885, DOI: 10.1016/j.enpol.2009.01.035.

(15) A Global Approach to Reducing Aviation Emissions; International Air Transport Association: Montreal, Canada, 2009; http://www.iata.org/SiteCollectionDocuments/Documents/Global_Approach_Reducing_Emissions_251109web.pdf.

(16) Destination 2025; United States Federal Aviation Administration: Washington, DC, 2011; http://www.faa.gov/about/plans_reports/media/Destination2025.pdf

(17) Renewable Fuels Standard; United State Environmental Protection Agency: Washington, DC, 2013; http://www.epa.gov/otaq/fuels/renewablefuels/index.htm.

(18) Falkenmark, M.; Rockström, J. The new blue and green water paradigm: Breaking new ground for water resources planning and management. J. Water Resour. Plan. Manage. **2006**, 132, 129−132.

(19) Gleick, P. Water and energy. Ann. Rev. Energy Environ. **1994**, 19 (1), 267−299.

(20) Chapagain, A. K.; Hoekstra, A. Y.; Savenije, H. H. G. Water saving through international trade of agricultural products. Hydrol. Earth Syst. Sci. Discuss. **2005**, 2, 2219−2251.

(21) Schnoor, J. L.; Doering, O. C. I.; Entekhabi, D.; Hiler, E. A.; Hullar, T. L.; Tilman, G. D.; Logan, W. S.; Huddleston, N.; Stoever, M. J. Implications of Biofuels Production in the United States; National Research Council: Washington, DC, 2008.

(22) Edwards, T. Alternative Aviation Fuels Evaluation to Support Certification; Air Force Research Laboratory: Wright-Patterson Air Force Base, 2011. http://www1.eere.energy.gov/biomass/pdfs/bio2011_edwards_3-5.pdf.

(23) Biofuels Issues and Trends; United States Energy Information Agency: Washington, DC, 2013; http://www.eia.gov/biofuels/issuestrends.

(24) Wu, M.; Mintz, M.; Wang, M.; Arora, S. Consumptive Water Use in the Production of Ethanol and Petroleum Gasoline; Argonne National Laboratory: Lemont, Il, 2009.

(25) Fingerman, K. R.; Torn, M. S.; O'Hare, M. H.; Kammen, D. M. Accounting for the water impacts of ethanol production. Environ. Res. Lett. **2010**, 5, 1−7, DOI: 10.1088/1748-9326/5/1/014020.

(26) Allen, D. T. et al. Framework and Guidance for Estimating Greenhouse Gas Footprints of Aviation Fuels; Air Force Research Laboratory: Wright-Patterson Air Force Base, 2009.

(27) Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) 2011; Argonne National Laboratory: Lemont, IL, 2011.

(28) Wang, M.; Huo, H.; Arora, S. Methods of dealing with co-products of biofuels in lifecycle analysis and consequent results with the U.S. context. Energy Policy **2011**, 39 (10), 5726−5736, DOI: 10.1016/j.enpol.2010.03.052.

(29) Speight, J. G. *The Chemistry and Technology of Petroleum*, 4th ed.; CRC Press: Boca Raton, FL, 2007.

(30) Wang, M.; Lee, H.; Molburg, J. Allocation of energy use in petroleum refineries to petroleum products: Implications for lifecycle energy use and emission inventory of petroleum transportation fuels. *Int. J. Life Cycle Assess.* **2004**, 9 (1), 34−44, DOI: 10.1065/lca2003.07.129.

(31) Gray, D.; White, C.; Tomlinson, G.; Ackiewicz, M.; Schmetz, E. Increasing security and reducing carbon emissions of the U.S. *In Transportation Sector: A Transformational Role for Coal with Biomass*; National Energy Technology Laboratory: Morgantown, MV, 2007.

(32) Bao, B.; El-Halwagi, M. M.; Elbashir, N. O. Simulation, integration and economic analysis of gas-to-liquid processes. *Fuel Process. Technol.* **2010**, 91, 703−713, DOI: 10.1016/j.fuproc.2010.02.001.

(33) Mantripragada, H. C. *Techno-economic evaluation of coal-to-liquids (CTL) plants and their effects on environment and resources*. Ph.D. Dissertation, Carnegie-Mellon University, Pittsburgh, PA, 2010.

(34) Aden, A.; Ruth, M.; Ibsen, K.; Jechura, J.; Neeves, K.; Sheehan, J.; Wallace, B.; Montague, L.; Slayton, A.; Lukas, J. *Lignocellulosic Biomass-to-Ethanol Process Design and Economics Utilizing Co-current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis for Corn Stover*; National Renewable Energy Laboratory: Golden, CO, 2002.

(35) Dias, M. O.; Ensinas, A. V.; Nebra, S. a.; Maciel Filho, R.; Rossell, C. E.; Maciel, M. R. W. Production of bioethanol and other bio-based materials from sugarcane bagasse: Integration to conventional bioethanol production process. *Chem. Eng. Res. Des.* **2009**, 87 (9), 1206−1216, DOI: 10.1016/j.cherd.2009.06.020.

(36) Ensinas, A. V.; Nebra, S. a.; Lozano, M. a.; Serra, L. M. Analysis of process stream demand reduction and electricity generation in sugar and ethanol production from sugarcane. *Energy Convers. Manag.* **2007**, 48 (11), 2978−2987, DOI: 10.1016/j.enconman.2007.06.038.

(37) Humbird, D.; Davis, R.; Tao, L.; Kinchin, C.; Hsu, D.; Aden, A. *Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol*; National Renewable Energy Laboratory, Golden, CO, 2011.

(38) Kumar, D.; Murthy, G. S. Impact of pretreatment and downstream processing technologies on economics and energy in ethanol production. *Biotechnol. Biofuels* **2011**, 4 (10), 27 DOI: 10.1186/1754-6834-4-27.

(39) Kwiatkowski, J. R.; McAloon, A. J.; Taylor, F.; Johnston, D. B. Modeling the process and costs of fuel ethanol production by the corn dry-grind process. *Ind. Crops Prod.* **2006**, 23 (3), 288−296, DOI: 10.1016/j.indcrop.2005.08.004.

(40) Lobo, P. C.; Jaguaribe, E. F.; Rodrigues, J.; da Rocha, F. A. A. Economics of alternative sugarcane milling options. *Appl. Therm. Eng.* **2007**, 27, 1405−1413, DOI: 10.1016/j.applthermaleng.2006.10.023.

(41) *Sugar Cane's Energy*, 2nd ed.; Macedo, I. d. C., Ed.; Uniao da Industria de Cana-de-Acucar (Brazilian Sugarcane Industry Association), 2007.

(42) Mei, F. *Mass and Energy Balance for a Corn-to-Ethanol Plant*, Masters thesis, Washington University, Saint Louis, MO, 2006.

(43) Mueller, S. *Detailed Report: 2008 National Dry Mill Corn Ethanol Survey*; University of Illinois at Chicago, Chicago, IL, 2010.

(44) Pearlson, M.; Wollersheim, C.; Hileman, J.; August, R. A techno-economic review of hydroprocessed renewable esters and fatty acids for jet fuel production. *Biofuels, Bioprod. Biorefin.* **2013**, 7, 89−96, DOI: 10.1002/bbb.1378.

(45) Phillips, S.; Aden, A.; Jechura, J.; Dayton, D. *Thermochemical Ethanol via Indirect Gasification and Mixed Alcohol Synthesis of Lignocellulosic Biomass*; National Renewable Energy Laboratory, Golden, CO, 2007.

(46) Shapouri, H.; Duffield, J. A.; Wang, M. *The Energy Balance of Corn Ethanol: An Update*; United States Department of Agriculture, Washington, DC, 2002.

(47) Sheehan, J.; Camobreco, V.; Duffield, J.; Graboski, M.; Shapouri, H. *Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus*; National Renewable Energy Laboratory, Golden, CO, 1998.

(48) Staples, M. Personal communication with Glenn Johnston, VP Gevo. Email, 2012.

(49) Staples, M. Personal communication with Hussain Abidi, Postdoctoral researcher at MIT. Email, 2012.

(50) Staples, M. Personal communication with Kevin Weiss, CEO Byogy Renewables Inc. Email, 2012.

(51) Staples, M. Personal communication with Wei Huang, VP LS9 Inc. Email, 2012.

(52) Vaswani, S. *Biodiesel from Algae*; SRI Consulting, Menlo Park, CA; 2009.

(53) Wang, M.; Wu, M.; Huo, H. Lifecycle energy and greenhouse gas emission impacts of different corn ethanol plant types. *Environ. Res. Lett.* **2007**, 2 (2), 1−13, DOI: 10.1088/1748-9326/2/2/024001.

(54) Fischer, G.; Nachtergaele, F. O.; Prieler, S.; Teixeira, E.; Toth, G.; van Velthuizen, H.; Verelst, L.; Wiberg, D. *Global Agro-ecological Zones (GAEZ v3.0) − Model documentation*; International Institute for Applied Systems Analysis: Laxenburg, Austria, 2009.

(55) Strzepek, K.; Baker, J.; Farmer, W.; Schlosser, C. A. *Modeling Water Withdrawal and Consumption for Electricity Generation in the United States*; MIT Joint Program on the Science and Policy of Global Change, Cambridge, MA, 2012.

(56) National Agricultural Statistics Service; United States Department of Agriculture: Washington, DC, 2013; http://quickstats.nass.usda.gov/.

(57) *Water Supply Stress Index Model*; United States Department of Agriculture Forest Service: Washington, DC, 2013; http://www.wassiweb.sgcp.ncsu.edu/.

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