

Accounting for the water impacts of ethanol production

This article has been downloaded from IOPscience. Please scroll down to see the full text article.

2010 Environ. Res. Lett. 5 014020

(<http://iopscience.iop.org/1748-9326/5/1/014020>)

[The Table of Contents](#) and [more related content](#) is available

Download details:

IP Address: 76.230.48.208

The article was downloaded on 10/03/2010 at 01:48

Please note that [terms and conditions apply](#).

Accounting for the water impacts of ethanol production

Kevin R Fingerman^{1,4}, Margaret S Torn^{1,2}, Michael H O'Hare³ and Daniel M Kammen^{1,3}

¹ Energy and Resources Group, University of California, Berkeley, 310 Barrows Hall, Berkeley, CA 94720-3050, USA

² Lawrence Berkeley National Laboratory, One Cyclotron Road, 90-1141, Berkeley, CA 94720, USA

³ Goldman School of Public Policy, University of California, Berkeley, 2607 Hearst Avenue, Berkeley, CA 94720-7320, USA

E-mail: kfingerman@berkeley.edu

Received 4 December 2009

Accepted for publication 22 February 2010

Published 9 March 2010

Online at stacks.iop.org/ERL/5/014020

Abstract

Biofuels account for 1–2% of global transportation fuel and their share is projected to continue rising, with potentially serious consequences for water resources. However, current literature does not present sufficient spatial resolution to characterize this localized effect. We used a coupled agro-climatic and life cycle assessment model to estimate the water resource impacts of bioenergy expansion scenarios at a county-level resolution. The study focused on the case of California, with its range of agroecological conditions, water scarcity, and aggressive alternative fuel incentive policies. Life cycle water consumption for ethanol production in California is up to 1000 times that of gasoline due to a cultivation phase that consumes over 99% of life cycle water use for agricultural biofuels. This consumption varies by up to 60% among different feedstocks and by over 350% across regions in California. Rigorous policy analysis requires spatially resolved modeling of water resource impacts and careful consideration of the various metrics that might act to constrain technology and policy options.

Keywords: biofuel, water, ethanol, life cycle assessment, LCA, energy policy

1. Introduction

Faced with erratic petroleum prices, security concerns, and climate change, governments across the globe have implemented policies aimed at increasing the volume of alternative fuels in the energy mix. These policies have helped lead to a six-fold increase in biofuel production over the past decade. Biofuels currently represent 1–2% of the global transport fuel and are projected to continue expanding rapidly (REN21 2008, IEA 2009).

The timeline laid out in the current version of the 2007 United States Energy Independence and Security Act (EISA) targets 9 billion gallons of renewable fuels for 2008 and 36 billion gal (or about 20% of total vehicle fuel consumption)

by 2022 (US Congress 2007). In a similar vein, the European Commission (EC) recently agreed to a proposal to increase its binding volumetric target to 10% renewables in the transport fuel mix and 20% of all energy by 2020 (UNCTAD 2008, European Commission 2009).

As production of biofuel continues to expand, especially given that this expansion is largely driven by policy, the environmental and social implications of these fuels have come under scrutiny, especially their life cycle greenhouse gas (GHG) emissions. Recognizing that emissions vary greatly depending upon feedstock and production methods (Farrell *et al* 2006) and that at least some biofuels have considerable 'indirect' emissions (for example, from remote land use change mediated through the international food market) (Hertel *et al* 2010, Searchinger *et al* 2008) many governments have begun promulgating policies using life cycle assessment (LCA) to

⁴ Author to whom any correspondence should be addressed.

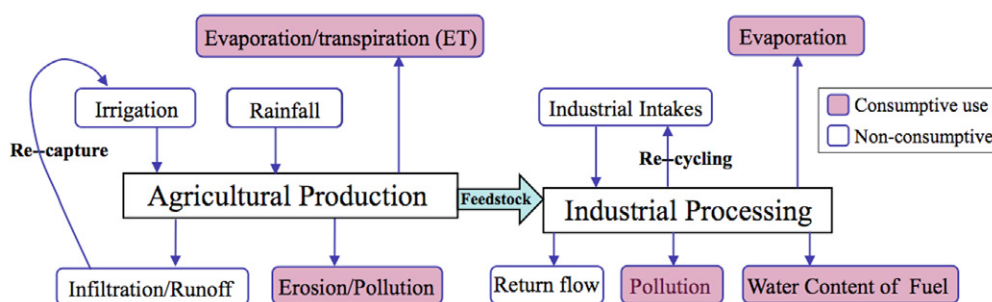


Figure 1. Schematic of water uses in the biofuel life cycle. Flows of water both into and out of the bioenergy production system are represented.

directly target a reduction in fuel GHG intensity. Examples of such regulations are California's Low Carbon Fuel Standard (LCFS) and the US federal Energy Independence and Security Act (EISA) of 2007.

Much less attention is being paid to water resources, but biomass energy carriers are usually orders of magnitude more water-intensive than conventional energy sources (King and Webber 2008, Chiu *et al* 2009, Gerbens-Leenes *et al* 2009, Wu *et al* 2009, Service 2009). This concern could be, as a report from the Institute for Agriculture and Trade Policy pointed out, the 'Achilles heel' of biofuel production (Keeney and Muller 2006).

1.1. Water scarcity

Population growth and dietary changes are projected to drive a 70–90% increase in demand for water worldwide in the next 50 years (Molden 2007), even as new supplies are dwindling. Concerns about environmental and social impacts have curtailed new reservoir construction while existing reservoirs are being lost to siltation and groundwater lost to overdraft at a rate of about 60–70 km³ yr⁻¹ (Serageldin 2001), or about half the capacity of Egypt's Aswan High Dam reservoir. By 2025, 1.8 billion people are predicted to be living in absolute water scarcity and 2/3 of all people to be experiencing some water stress (UNEP 2007).

1.2. Water and biofuels

Water is consumed all along the biofuel supply chain. Figure 1 shows the major uses of water in both the agricultural and industrial phases of biofuel production. Some of the water applied as irrigation runs off or infiltrates and is later available for other productive uses. Furthermore, some of the water consumed in agricultural production is so-called 'green water'—naturally available soil moisture. To avoid confusion, and to provide a comprehensive accounting of water use, this analysis uses a common definition of *water consumption*; water is considered consumed if it is removed from any potential further use for the remainder of one hydrologic cycle.

Two types of consumption are considered in this analysis:

- *Evapotranspiration (ET)*—combination of evaporation and transpiration.

- *Industrial/biorefinery consumptions*—water consumed in industrial processes through uses such as cooling and incorporation into finished products.

Many studies of the water resource impacts of biofuel production only consider uses at the biorefinery (NRC 2007, Keeney and Muller 2006). While industrial consumption is important, especially for local water resources, this method does not account for agricultural water consumption and therefore does not fully characterize the life cycle effect of biofuels on water resources.

Some recent studies (King and Webber 2008, Chiu *et al* 2009, Service 2009, Wu *et al* 2009) include agricultural consumption in their analyses, but only account for water that is applied to fields through irrigation. Considering only irrigation water implies that the 80% of global agriculture, and 85% of US corn production, that is exclusively rainfed consumes no water. While irrigation water is a vital resource, rainwater is also of value, and if not devoted to biofuel feedstock production could be allocated to other crops, to environmental services, or to reservoir and/or groundwater recharge (Molden 2007).

In studies considering all evapotranspiration (Gerbens-Leenes *et al* 2009), lack of spatial resolution leads to an illusion of uniformity in what is actually a very heterogeneous system. Owing to differences in crop physiology, management, energy yield, and climate, the amount of water required to produce a gallon of biofuel varies spatially. Furthermore, because water availability also varies over space and time, the implications of consuming a given volume of water will not be uniform. This is an important difference between water resource impacts and GHG emissions, which have essentially uniform and widespread effect wherever and whenever they occur.

In this paper we develop a quantitative framework for evaluating the water resource effects of biofuel expansion for use in LCA and policy analysis. We take as a case study the state of California, which has been a leader in the development of LCA-based fuel policies and which, through its wide variety of agricultural systems and climate types, allows us to draw robust and broadly applicable conclusions. California is also facing severe water supply and allocation challenges. We propose a list of quantitative metrics to enable rigorous analysis of the water impacts of bioenergy production and policy for a variety of concerns and contexts.

2. Experimental methods

We used the Penman–Monteith model, a well-established crop evapotranspiration model that uses plant physiology and climate data to calculate water consumption on a daily time-step (Allen *et al* 1998). These calculations were performed at a county-level resolution in order to capture the spatial heterogeneity of water resource requirement for bioenergy production in California. The calculated ET was then incorporated into a life cycle assessment of biofuel water consumption.

2.1. Evapotranspiration modeling

Crop water consumption is estimated in many studies by calculating ET using the Penman–Monteith model developed by the UN Food and Agriculture Organization (Allen *et al* 1998, Chapagain and Hoekstra 2004, Hoekstra and Chapagain 2007, Gerbens-Leenes *et al* 2009). As shown in equation (1), Penman–Monteith estimates ET as the product of a reference crop evapotranspiration (ET_o) and a crop coefficient (K_c). ET_o characterizes climate effects and is calculated from temperature, solar radiation, wind speed, and relative humidity. K_c accounts for the effect of characteristics such as crop height, surface coverage, and albedo, that distinguish a crop from the reference surface (Allen *et al* 1998).

$$ET_c = K_c \times ET_o \quad (1)$$

where ET_c is total evapotranspiration (mm day^{-1}) from crop c ; K_c is a physiological crop constant that varies from 0 to 1; and ET_o is reference crop evapotranspiration (mm day^{-1}), representing ET from a grass surface of 0.12 m height that is calculated as follows (equation (2)).

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma(900/(T + 273))u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (2)$$

where: Δ = slope of the vapor pressure curve ($\text{kPa } ^\circ\text{C}^{-1}$); T = average air temperature ($^\circ\text{C}$); γ = psychrometric constant ($\text{kPa } ^\circ\text{C}^{-1}$); e_s and e_a are saturation and actual vapor pressure, respectively (kPa); R_n = net radiation at the crop surface ($\text{MJ m}^{-2} \text{day}^{-1}$); G = soil heat flux ($\text{MJ m}^{-2} \text{day}^{-1}$); u_2 = wind speed at 2 m (m s^{-1}).

We applied the Penman–Monteith model, to calculate crop embedded water, using the Consumptive Use Program (CUP)—the Penman–Monteith model parameterized and refined for California by the California Department of Water Resources. This model has been validated using nine years of data from the instrumentation network of the California Irrigation Management Information System (Orang *et al* 2005). CUP uses measured monthly solar radiation, maximum, minimum, and average temperature, dew point, and wind speed to compute ET_o for climatic regions within California. K_c values are adapted from values published by the United Nations Food and Agriculture Organization (Doorenbos and Pruitt 1984, Allen *et al* 1998) for analogous crop types. We did not apply a stress coefficient (K_s). In other words, we estimated ET for standard conditions, which assumes crops

achieve full production for the given climate (Allen *et al* 1998). Under water stress, both ET and yield will be reduced, such that the ET/yield ratio reported here is not expected to be highly sensitive to water stress above the wilting point.

2.2. Production scenarios

Increased ethanol production could be met in a variety of ways. In the US, common energy crops include corn, other grains, and sugar beets. Possible second-generation feedstocks include agricultural waste, municipal solid waste, and dedicated biomass energy crops such as switchgrass and miscanthus.

County-level agricultural production and per-acre productivity data used in this study are drawn from the USDA National Agricultural Statistics Service's (NASS) agricultural census. NASS county-level production data are also used for weighting of statewide averages. All counties in California were used in the study, though individual feedstocks were only considered in those counties where they (or comparable crops in the case of biomass feedstocks) are currently grown.

We assume that field crops will be displaced for feedstock production—specifically corn, wheat, rice, sorghum, barley, oats, cotton, beans, and fodder crops. These are low value crops, and are therefore more likely to be replaced by biofuel feedstocks than are higher value crops such as fruits and vegetables.

Data on refining processes and outputs are drawn from the EBAMM model (Farrell *et al* 2006), the GREET model (Wang 2009), and the NREL model biorefinery (Aden *et al* 2002).

2.2.1. Case-study feedstocks. We modeled four feedstock types: corn, sugar beet, a low-yield biomass energy crop (LYB) similar to the low-input high-diversity grasslands investigated by Tilman *et al* (2006) and a high-yield biomass crop (HYB) representing dedicated energy crops such as miscanthus.

Corn grain is the primary feedstock for biofuel production in the United States. In California, plantings rose almost 30% between 2006 and 2008 (USDA 2008) with the majority of production going to supply the state's livestock operations. California produces among the highest sugar beet yields globally; only 25 000 acres were dedicated to sugar beet cultivation in the state in 2009 but this figure could expand to exceed the 1970 high of 300 000 acres (USDA 2008).

No sufficiently broad field tests of perennial grasses such as miscanthus (*Miscanthus giganteus*) and switchgrass (*Panicum virgatum*) to date provide reliable data on their water productivity. Furthermore, existing crop evapotranspiration models are calibrated for current crop systems and have not yet been applied to most biomass crops. As a result, this analysis uses two hypothetical biomass crop feedstocks—one low-yield and one high-yield—using outside data to project biomass yield, water consumption, and ethanol productivity.

The low-yield biomass (LYB) crop is modeled here on grassy fodder crops (hay and haylage) currently grown in the state. Similar to lignocellulosic feedstock crops, fodders have been bred and cultivated to maximize total plant biomass rather than one specific plant product as is the goal with most crops.

The average productivity of these crops is approximately 8.2 dry tonnes of biomass per hectare annually—similar to the yields anticipated from low-input high-diversity grasslands (Tilman *et al* 2006).

High-yield biomass (HYB) crops in this analysis are modeled as producing 20 dry tonnes of biomass per hectare on average annually after Williams (2006) with the relative yields in various California regions modeled on common biomass crops currently grown in the state. This is comparable to yields predicted for energy crops such as miscanthus (Hastings *et al* 2009). The water consumption dynamics of these hypothetical HYB crops are modeled using biomass crop water use efficiency values developed by Berndes (2002).

2.2.2. Case-study exclusions. We did not analyze the embedded water in agricultural residues used as a feedstock because there was no established method or empirical constraints for allocating embedded water among products and coproducts. Sugarcane, while a major feedstock for ethanol production globally, is not grown widely in California and so is not analyzed here. Biodiesel is also not considered because soy, the primary agricultural feedstock for biodiesel in the US, is grown in such small quantities in California that its area is not reported in the USDA agricultural census.

We do not take into account indirect effects of feedstock production on water resources in which water consumption is altered far from the production site by market-mediated land use change (Searchinger *et al* 2008, Hertel *et al* 2010). A standard method for their quantification has not been developed and is the subject of much debate. Also, although pollution can reduce the amount of available water, we did not evaluate it here.

3. Results

In all the feedstock cases studied, the agricultural production phase represented more than 99% of life cycle water consumption on average with biorefineries consuming less than 1% of total ethanol embedded water. Our analysis shows a clear difference in fuel embedded water among the feedstocks modeled. Table 1 shows the average embedded water in ethanol from each of the feedstock crops weighted by county feedstock production (equation (3)). The statewide average embedded water in ethanol from the feedstocks studied varied by more than 50% due to plant physiological properties and where individual feedstocks are grown.

$$\sum_{i,c} ET_{ic} \left(\frac{y_{ic}}{Y_c} \right) \quad (3)$$

where i = county; c = feedstock crop; ET_{ic} = evapotranspiration of crop c in county i (L H₂O/L ethanol), y_{ic} = yield of crop c in county i , and Y_c = total yield of crop c in California.

The production-weighted averages presented in table 1 are derived from a dataset exhibiting substantial county-level heterogeneity in both yield and crop ET. Figure 2 illustrates the breadth of values seen for these crop characteristics.

Table 1. Water embedded in ethanol produced in California (L H₂O/L EtOH). Production-weighted average of county-scale water intensity estimates.

Feedstock	ET (L H ₂ O/L EtOH)	Refinery (L H ₂ O/L EtOH)
Corn grain	1533	3.6 ^a
Sugar beets	1271	3.6 ^a
Low-yield biomass	1301	6 ^b
High-yield biomass	916	6 ^b

^a Wu *et al* (2009). ^b Aden *et al* (2002).

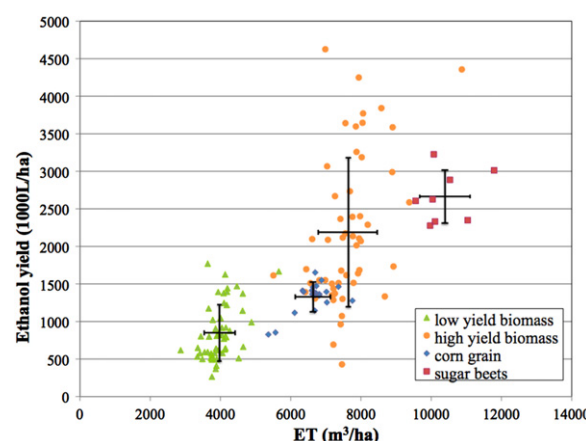


Figure 2. ET and yield by county. Each data point represents a feedstock in a county where it is currently grown. The error bars show the standard deviation about the mean among counties for each feedstock type; the bars cross at the mean value for both parameters.

The feedstocks studied varied in both their water consumption and their yield per hectare. This result leads to both spatial and feedstock-related variation in water consumption per MJ of fuel produced. The variation stems from climatic factors such as temperature, wind, and relative humidity within the study area as well as from physiological differences among the feedstock crops studied. Water consumption ranged from less than 1 acre foot yr⁻¹ for cultivation of low-yield biomass in Modoc County to more than 4 acre feet yr⁻¹ for cultivation of sugar beets in Imperial County. Ethanol yield ranged even more dramatically, from less than 1000 L ha⁻¹ for low-yield biomass in Sierra County to almost 14 000 L ha⁻¹ from high-yield biomass in Imperial County.

This variation in yield and ET among counties creates patterns in the geographic variation of water consumption. Figures 3(a) and (b) focus on the low-yield biomass feedstock because it is grown in every county in the state. Figure 3(a) presents the water consumed per liter of fuel from each of these places, while figure 3(b) shows the amount consumed per hectare cultivated. The contrasting patterns of these two maps stem from the fact that while more water is consumed in cultivation of this crop in the southern reaches of the state, those areas are also more productive per unit consumption. Imperial County in Southern California was found to have both the highest water consumption of any county in the state and the greatest yield.

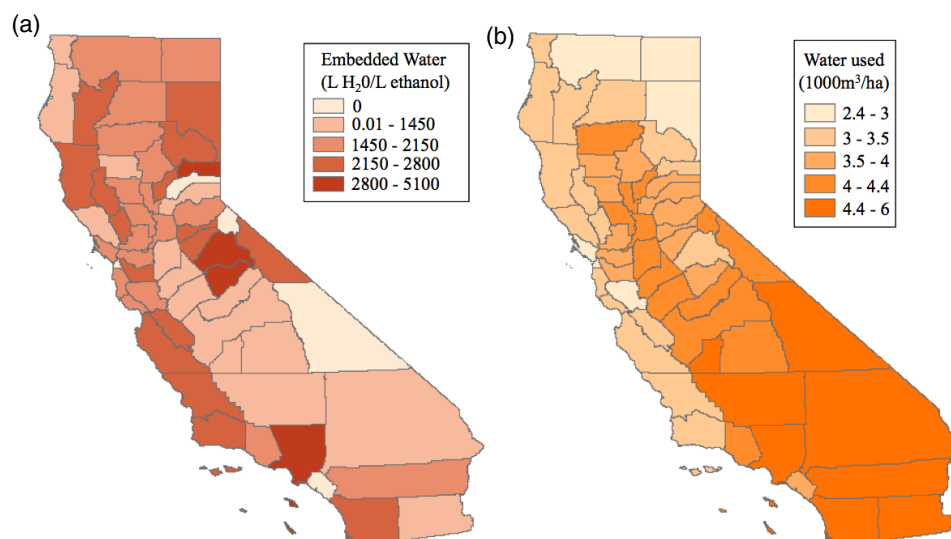


Figure 3. (a) Embedded water in ethanol from low-yield biomass feedstock. (b) Yearly per hectare water consumption for cultivation of low-yield biomass feedstock.

If regional average field crops were displaced by biofuel feedstocks, there would be a decrease in total water demand statewide, since some of those displacements would occur on land previously occupied by very water-intensive crops such as rice and alfalfa. If these heavily irrigated crops were *preferentially* displaced, the water savings would be significant. If, however, the bioenergy targets were met through expansion of irrigated agriculture, the net increase in water demand would be substantial.

4. Discussion

The amount of water required to produce ethanol from purpose-grown feedstocks in California was found to range from under 500 L of water per liter of fuel to over 3500. In comparison, production of a comparable (by energy content) volume of gasoline requires from 2.1 L of water for conventional petroleum crude to almost 14 L for fuel from tar sands (King and Webber 2008, Gleick 1994).

It would be overly simplistic, however, to compare these figures directly—concluding that petroleum fuels are over 100 times more water-efficient than is ethanol. While industrial processing of biofuels and petroleum fuels require comparable amounts of water, biofuels also require water for the cultivation of feedstocks, whereas the feedstock for petroleum refining is pumped from the earth. Although over 99% of the water ‘embedded’ in an agricultural biofuel is used in feedstock cultivation, this consumption is much more spatially diffuse than the refining of the feedstock into biofuel. Feedstocks, grown over a large area, are concentrated in one locale to be refined into biofuel. As a result, in some cases effects on the *local* resource base may be larger from the industrial phase of the biofuel life cycle than from the agricultural phase.

Furthermore, a new refinery, whether for biomass or petroleum refining, represents a *new* demand on water resources. In contrast, feedstock production may result in an

increase or a decrease in water demand depending on what, if anything, is replaced. In cases where the energy crops displace more water-intensive cultivation, this shift could lead to a net decrease in local water consumption.

Location of water consumption is also an important consideration. For example, cultivation of rainfed crops in tropical regions where water is plentiful may not result in water scarcity although it may consume a great deal of water. In contrast, use of scarce groundwater for refining petroleum in arid regions where it is produced might put excessive strain on that resource base even though it may be comparatively ‘efficient’ in simple terms of water consumption per unit energy. This is an important difference between analyses of life cycle water consumption, and those of GHG emissions; use of water has very different implications in different contexts, whereas GHG emissions have essentially the same effect wherever they are produced.

4.1. Functional units for analysis

Life cycle assessment (LCA) requires that impacts be normalized and reported in terms of a common ‘functional unit’. Current literature on bioenergy water consumption implicitly assumes that impacts on water resources can be normalized and compared through the use of a single metric. Metrics considered have included gal H₂O applied per mile traveled (King and Webber 2008), L H₂O applied per L ethanol (Chiu *et al* 2009), m³ H₂O consumed per GJ ethanol (Gerbens-Leenes *et al* 2009), and gal H₂O applied per gal ethanol (Wu *et al* 2009). One of the important messages of our research is that in moving the energy system to use water more responsibly, different measures of consumption will be important in different contexts and that there is no one consistently superior functional unit for analysis.

While the ‘water footprint’ of a biofuel can be calculated in terms of L H₂O consumed per MJ, in assessing the effects of a production system we may at times be concerned with

Table 2. Functional units for life cycle assessment of water resource effects of biofuel feedstock production. Included are the *analytical utility* of each metric, as well as the *context* and *scale* in which each might be used as a basis for optimization and the *assumptions* embedded in doing so.

Unit	Analytical utility	Context	Scale	Embedded assumptions
		For use as a basis for optimization		
L H ₂ O consumed/MJ fuel produced	Compare to overall water resource base with other energy carriers	Water productivity (\$m ⁻³ consumed); 'water footprint'	Basin, region	All water consumed is of equal importance
L H ₂ O applied/MJ fuel produced	Compare to alternate uses of the resource	Irrigated regions with stressed irrigation resources; energy inputs to fuel production	Field, basin, irrigation district	Irrigation water is of primary importance. Rainfed crops consume no water
L H ₂ O consumed/ha	Compare to precipitation to determine irrigation demand or environmental flows	Where resource is limited for environmental flows/groundwater	Field, basin	Water conservation is more important than maximizing derived value
L H ₂ O applied/ha	Compare to regional average water demand	Where many farms/farmers rely on the same resource	Basin, irrigation district	Equity of distribution is of greater value than overall optimization of water productivity
Pollution impact/MJ fuel produced	Evaluate life cycle pollution impact insofar as this can be quantified	Resource/environment stressed by industrial effluent or agricultural runoff	Field, basin, region	

ascertaining the volume of water consumed per *hectare* used to grow feedstock. These two metrics can lead to very different pictures of the production system as is illustrated by figures 3(a) and (b). If our interest lies in optimizing the former, figure 3(a) would indicate that we should focus production in the southern reaches of California. If, however, we are interested in the equity of resource distribution, or in minimizing the energy-intensive pumping of water across great distances, figure 3(b) would indicate that production in the northern reaches of the state is the more viable option.

The dichotomy illustrated in figures 3(a) and (b) reveals the importance for water resource analysis of choosing the proper functional unit for analyzing the issue at hand. Table 2 presents many of the metrics that might be of value and concern in evaluating the water resource implications of biofuel production. It lays out the analytical utility of each metric, as well as the context and scale in which each might be used as a basis for optimization and the assumptions embedded in doing so.

A critical issue relating to these metrics is whether the sustainability of water resource management hinges on the metric of L H₂O *consumed* per unit product (in this case MJ of ethanol) or on L H₂O *applied* per unit product. The latter metric's focus only on irrigation application implies that rainfed crops consume no water, which is clearly not the case. Rainwater is a valuable resource that could be dedicated to other productive use, to environmental services, or to aquifer recharge if not consumed in biofuel feedstock cultivation (Molden 2007). On the other extreme, some researchers argue that evapotranspiration should be the primary or exclusive metric of concern, since irrigation water can run off or infiltrate to rejoin the exploitable resource base. While

this may be true on a macroscale, in many localities water that is applied inefficiently is lost to productive use, causing irrigation demand to be a more important concern than total ET.

No unit is *de facto* best for analysis and optimization of water resources in the bioenergy system. Instead, local nuance must be accounted for if policies are to adequately address this important implication of bioenergy expansion.

4.2. Policy implications

Biofuel policies aimed at reducing life cycle GHG emissions are a step in the right direction, but many policy makers are beginning to recognize that a fuel with a life cycle GHG footprint better than that of its petroleum analog is not necessarily environmentally benign (Verdonk *et al* 2007, Schlegel and Kaphengst 2007, Hecht *et al* 2009).

In some cases, optimizing a biofuel production system with regard to greenhouse gas emissions could increase the strain on water resources. For example, the developing understanding of market-mediated or 'indirect' land use change (Searchinger *et al* 2008, Fargione *et al* 2008) may cause production of biofuel feedstocks to trend away from currently cultivated land. This could mean extensification of agriculture, potentially bringing new strain on irrigation water resources. Furthermore, the imperative to increase yields in order to minimize cropland required for biofuel could cause growers to irrigate cellulosic crops such as miscanthus, which are currently grown in rainfed conditions.

Water resource implications of bioenergy policies should be considered in the rule-making process to ensure that these policies do not drive changes that will put undue stress on

water supply. We recommend the following actions and further research to analyze and elaborate them into practical form:

- *Implement a water accounting system.* Our analysis shows the feasibility of calculating the water embedded in biofuels from different feedstocks grown in various regions.
- *Establish water intensity regulations for low-carbon fuels.* Calculated or reported water consumption and application for biofuel production should be incorporated into regulatory frameworks with incentives for implementing best management practices.
- *Regulate siting and design of biorefineries.* While water consumption by biorefineries is a relatively small portion of total biofuel embedded water, it may have a large local effect. Careful siting and design of biorefineries will minimize conflicts between different water uses.

Acknowledgments

We acknowledge the invaluable contributions of our late colleague Alex Farrell who initiated this research.

We thank Sonia Yeh and Richard Snyder (UC Davis), Morteza Orang and Scott Hayes (CA Department of Water Resources), Jim McKinney (California Energy Commission). Funding was provided by the Energy Biosciences Institute and the California Air Resources Board, whose positions are not necessarily represented herein.

References

- Aden A, Ruth M, Ibsen K, Jechura J, Neeves K, Sheehan J, Wallace B, Montague L and Slayton A 2002 *Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis for Corn Stover* (Golden, CO: National Renewable Energy Laboratory)
- Allen R G, Pereira L S, Raes D and Smith M 1998 *Crop Evapotranspiration—Guidelines for Computing Crop Water Requirements*, FAO Irrigation and Drainage Paper 56 (Rome: Food and Agriculture Organization of the United Nations)
- Berndes G 2002 Bioenergy and water—the implications of large-scale bioenergy production for water use and supply *Glob. Environ. Change* **12** 253–71
- Chapagain A and Hoekstra A 2004 *Water Footprints of Nations* (Delft: UNESCO-IHE)
- Chiu Y-W, Walseth B and Suh S 2009 Water embodied in bioethanol in the United States *Environ. Sci. Technol.* **43** 2688–92
- Doorenbos J and Pruitt W 1984 *Crop Water Requirements* (Rome: FAO)
- European Commission 2009 Directive on the promotion of the use of energy from renewable sources, Brussels
- Fargione J, Hill J, Tilman D, Polasky S and Hawthorne P 2008 Land clearing and the biofuel carbon debt *Science* **319** 1235–7
- Farrell A, Plevin R, Turner B, Jones A, O'Hare M and Kammen D 2006 Ethanol can contribute to energy and environmental goals *Science* **311** 506
- Gerbens-Leenes W, Hoekstra A and Van Der Meer T 2009 The water footprint of bioenergy *Proc. Natl Acad. Sci.* **106** 10219
- Gleick P H 1994 Water and energy *Ann. Rev. Energy Environ.* **19** 267–99
- Hastings A, Clifton-Brown J, Wattenbach M, Mitchell C and Smith P 2009 The development of MISCANFOR, a new Miscanthus crop growth model: towards more robust yield predictions under different climatic and soil conditions *GCB Bioenergy* **1** 154–70
- Hecht A D, Shaw D, Bruins R, Dale V, Kline K and Chen A 2009 Good policy follows good science: using criteria and indicators for assessing sustainable biofuel production *Ecotoxicology* **18** 1–4
- Hertel T W, Golub A, Jones A D, O'Hare M, Plevin R J and Kammen D M 2010 Global land use and greenhouse gas emissions impacts of US maize ethanol: estimating market-mediated responses *BioScience* **60** 223–31
- Hoekstra A Y and Chapagain A K 2007 Water footprints of nations: water use by people as a function of their consumption pattern *Water Resour. Manage.* **21** 35–48
- International Energy Agency 2009 Statistical database, www.iea.org/stats/, accessed Dec. 1, 2009
- Keeney D and Muller M 2006 *Water Use by Ethanol Plants: Potential Challenges* (Minneapolis, MN: Institute for Agriculture and Trade Policy)
- King C W and Webber M E 2008 Water intensity of transportation *Environ. Sci. Technol.* **42** 7866–72
- Molden D 2007 *Water for Food, Water for Life: a Comprehensive Assessment of Water Management in Agriculture* (London: Earthscan/James & James)
- National Research Council 2007 *Water implications of biofuels production in the United States* ed J L Schnoor (Washington, DC: National Academies)
- Orang M, Snyder R and Matyac S 2005 CUP (Consumptive Use Program) model *California Water Plan Update 2005: A Framework for Action* (Sacramento, CA: California Department of Water Resources)
- REN21 2008 *Renewables 2007 Global Status Report* Paris; Washington, DC, REN21 Secretariat; Worldwatch Institute; Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ)
- Schlegel S and Kaphengst T 2007 European Union policy on bioenergy and the role of sustainability criteria and certification systems *J. Agric. Food Indust. Organ.* **5** 7
- Searchinger T, Heimlich R, Houghton R A, Dong F, Elobeid A, Fabiosa J, Tokgoz S, Hayes D and Yu T-H 2008 Use of US croplands for biofuels increases greenhouse gases through emissions from land use change *Science* **319** 1238–40
- Serageldin I 2001 Assuring water for food: the challenge of the coming generation *Int. J. Water Resour. Dev.* **17** 521–5
- Service R F 2009 Another biofuels drawback: the demand for irrigation *Science* **326** 516–7
- Tilman D, Hill J and Lehman C 2006 Carbon-negative biofuels from low-input high-diversity grassland biomass *Science* **314** 1598–1600
- United Nations Conference on Trade and Development 2008 *Making Certification Work for Sustainable Development: the Case of Biofuels* (Geneva: United Nations) UNCTAD/DITC/TED/2008/1
- United Nations Environment Program 2007 *Global Environmental Outlook (GEO) 4* (Nairobi: United Nations)
- US Congress 2007 Energy Independence and Security Act of 2007
- USDA 2008 *National Agricultural Statistics Service—2007 Census of Agriculture*
- Verdonk M, Dieperink C and Faaij A P C 2007 Governance of the emerging bio-energy markets *Energy Policy* **35** 3909–24
- Wang M Q 2009 *The GREET Spreadsheet Model: Greenhouse Gases and Regulated Emissions and Energy Use in Transportation, Version 1.8c* Center for Transportation Research, Energy Systems Division, Argonne National Laboratory
- Williams R B 2006 *Central Valley and California Lignocellulosic Ethanol Potential: Summary Analysis* (Davis, CA: California Biomass Collaborative/CEC)
- Wu M, Mintz M, Wang M and Arora S 2009 *Consumptive Water Use in the Production of Ethanol and Petroleum Gasoline* Argonne National Laboratory (ANL)