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Evaluation of water use for bioenergy at different scales

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Abstract: This perspective reviews water metrics for accounting total water demand to produce bioenergy at various spatial scales. Volumes of water abstracted, consumed, and altered are estimated to assess water requirements of a bioenergy product, providing useful tools for water resource management and planning at local, regional, and global scale. Blue-water use accounting, integrated over time and space, provides the most direct measurements of the effects of bioenergy production on freshwater allocation among various end-users, and on human and ecosystem health and well-being. Measurement of total water demand for crop evapotranspiration, which includes both blue and green water, communicates vital information of how land and water productivity supports/constrains bioenergy expansion, and helps identify potential areas to increase the productivity of agriculture through improved soil and water conservation, changes in crop choice, and improved crop management. Life-cycle water use accounting provides a useful comparison of water required for production and conversion of feedstock to various forms of energy, and opportunities to improve water use efficiency throughout the supply chain. In addition, life-cycle water use may be used to account for water use *avoided* as a result of displacement of products by coproducts of biofuel production; though these applications must be interpreted with caution. Local or regional conditions and the objective of the analysis at hand determine which water accounting metrics are most relevant and the relative importance of water use impact compared to other impacts, such as impacts to soil quality and biodiversity. © 2011 Society of Chemical Industry and John Wiley & Sons, Ltd

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Introduction

The growing literature characterizing bioenergy-water links, using metrics such as 'embedded water', 'water footprint (WF)', or 'consumptive water use' of bioenergy has helped to raise awareness of the increasing water demand to meet bioenergy production.[1–6] However, generally valid quantifications of the influence of bioenergy on water are complicated because of the multitude of existing and rapidly evolving bioenergy sources; complexities of physical, chemical, and biological conversion processes; feedstock diversity and variability in site-specific conditions. Drawing sufficiently general understanding of the impact of bioenergy on water from existing literature is hampered by the differences in their scope, system boundaries, definitions of water use, and methods employed.

This perspective provides a review of the different types of metrics used to evaluate water use, focusing on their value as tools to better understand the water demands of bioenergy production. Case studies of bioenergy production using various feedstocks at different locations and spatial scales illustrate appropriate uses of these accounting tools and highlight their usefulness within specific contexts. The caveats of their uses and need for future development are summarized at the end.

The concept of water use

Overview

Literature on water requirements of bioenergy consists largely of volumetric assessments of the water required to produce biomass and convert it to solid/liquid/gaseous fuels that are subsequently used as transportation fuels or for generation of heat and electricity. Assessment includes volumes of water abstracted, consumed and/or altered.* Studies may concentrate on only part of the bioenergy supply chain or consider the entire life-cycle. Table 1 summarizes selected water use metrics commonly used in the literature.

Water use and the associated effects on water flows and ecosystems are measured by various metrics, depending on the water source, removal from the water cycle via evaporation or transpiration, and qualitative alteration (degradation). For definition of green water (GW) and blue water (BW), we adopt the definition in Hoff *et al.*[7]

> *Following the definition of Rockström et al.,[8] green water is the soil water held in the unsaturated zone, formed by precipitation and available to plants, while blue water refers to liquid water in rivers, lakes, wetlands and aquifers, which can be withdrawn for irrigation and other human uses. Consistent with this definition, irrigated agriculture receives blue water (from irrigation) as well as green water (from precipitation), while rain-fed agriculture only receives green water. Rainwater harvesting is at the interface of blue and green water. Catching runoff and storing it in small reservoirs (or possibly underground) is interpreted as blue water management, enhancement of infiltration and storage of rain in soil as green water management.'*

BW withdrawn from surface bodies and aquifers is used both consumptively and non-consumptively. Consumptive use removes water from the current hydrological cycle through evaporation, evapotranspiration and product incorporation. By definition, consumption implies that water consumed is not immediately available for use by humans and the ecosystem in the watershed from which water is originally withdrawn. BW used non-consumptively is released back to the environment with or without change in quality, and is available for downstream uses, such as agriculture, industry, and human consumption. Unlike BW, GW use is considered only in a consumptive sense, but modification of GW or soil water storage can influence BW availability.

Water use requirement is typically expressed as the amount of water use per unit of bioenergy produced (often referred to as *water intensity*). The reciprocal of intensity, i.e. the amount of bioenergy produced per unit of water use is often referred to as *water productivity*. Bioenergy produced may be expressed in terms of energy content, volume, or vehicle distance traveled, if used as liquid transportation fuel or to provide power for electric vehicles.

* The term 'bioenergy production' is used here to summarize the various ways of producing biomass and converting it to different solid, liquid and gaseous fuels, and to electricity. However, it is recognized that this term is not doing justice to the first law of thermodynamics, which states that energy can be neither created nor destroyed, but only change forms.

  | *Biofuels, Bioprod. Bioref.* 5:361–374 (2011); DOI: 10.1002/bbb

Table 1. Selected water use metrics used in literature.

Indicator	Description (studies can use slightly different definitions)	Selected relevant literature	Case study presented here (country and scale)
Water use metrics			
Water withdrawal (off-stream use)	Water removed from the ground or diverted from a surface-water source for use.	King and Webber;[12] Dominguez-Faus *et al.*[59]	Sugarcane (Brazil, –field + feedstock processing)
Consumptive water use	Includes water use due to evaporation, transpiration and product incorporation. When the water use during a products life-cycle is assessed, evaporative losses during post harvest processing can be included (see Life-cycle water use). Can also include water withdrawal not returning to the same catchment area or not returning in the same time period.	Includes 'green water' and 'blue water' consumptive use. Berndes.[1] Referred to as blue and green water footprint by Gerbens-Leenes *et al.*[3]	Bioenergy feedstock (global – field level)
Degradative water use	Withdrawal and discharge into the same watershed after the quality of the water has been (significantly) degraded.	Pfister *et al.*[14]	
Grey water use	The volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards.	Gerbens-Leenes *et al.*[3]	
Life-cycle water use	Water consumed/withdrawn throughout the life-cycle of biomass based fuels (including their end use). May credit bioenergy due to co-products produced.	King and Webber;[12] Chiu *et al.*;[13] Pfister *et al.*;[14] Chapagain and Orr,[33] Mishra and Yeh,[24] Ridoutt and Pfister [25]	Corn (US- varies from field to state level when conveyance loss and co-products displacement are considered)
Water flows balances			
Crop water balance	Evaluates the water balance of cultivated soils. Results are expressed in flux per unit surface area, in mm/period, or in (m^3/ha) per period.		Jatropha (India - field level)
Hydrologic balance	Express various elements of water balance of land or water basin (m^3/yr). Results include hydric deficit, annual/dry-period withdrawal and annual/winter drainage.	Bonnet and Lorne[4]	

Productive versus non-productive water use

Metrics measuring water use requirement could potentially classify such use as productive and non-productive as indicated in Fig. 1. Productive water use supports activities for agricultural and bioenergy production. Increasing productive water use for bioenergy system can be achieved by (i) reducing non-productive evaporation and consumptive uses at the field and production plant throughout the supply chain; and/or (ii) improving the management and planning of productive consumptive and non-consumptive water use, including improving the productivity across a range of agricultural management regimes from rain-fed crops to irrigated crops.[9]

Figure 2 presents an overview of rainfall partitioning on field level. If non-productive evaporation is reduced in favor of plant transpiration, total biomass harvest may increase without necessarily increasing the pressure on downstream freshwater resources. This can be achieved both through changed soil and water management [9] – including water harvesting – and through the introduction of suitable bioenergy crops that allows more effective water use.[4] For instance, some plants that are suitable as bioenergy feedstock, are also drought-tolerant, and have relatively high water use productivity can be grown in areas not suitable for conventional food and feed crops (see case study on Jatropha cultivation in India). Plants that are cultivated in rotations with conventional crops can also make better use of rain falling outside the growing season of conventional crops.[9]

Water use categories

Accounting of water use (consumptive or non-consumptive; productive or non-productive) is generally achieved by using the volume of water use, i.e. m^3. Various water use categories identified in the literature are now reviewed.

	Consumptive uses	Non-consumptive uses
Productive evaporation use	• Crop ETc • Water harvested with crop	• Deep percolation for salt leaching • Frost control
Non-productive evaporation use	• Evaporation from soil surface, open ditches, conveyance channels, and crop canopy, etc. • Sprinkler evap. • Reservoir evap.	• Excess run-off and seepage looses • Excess deep percolation

Figure 1. Schematic diagram of the distinction between different types of water use in a production system modified from Burt *et al*.[10] Excess runoff may be consumptive if water is discharged to watershed different from withdrawal point.

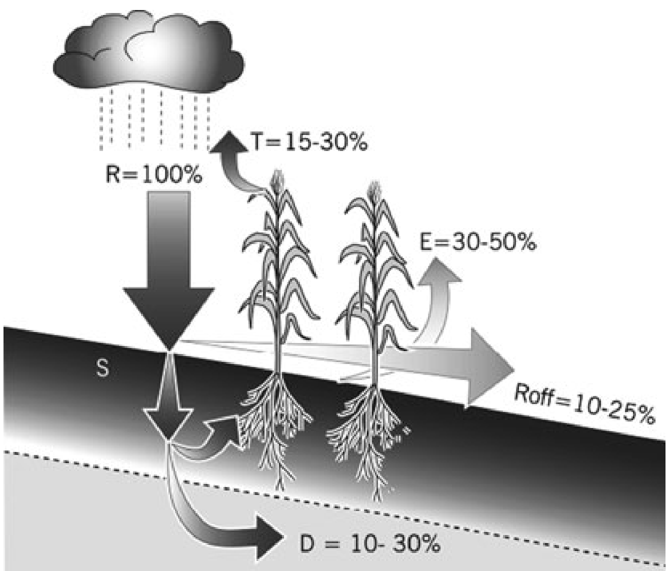

Figure 2. A general overview of rainfall (R) partitioning. Runoff (Roff) and drainage (D) are lost from the farmer's field, but can be used downstream, although part of the runoff can be lost to evaporation as it flows through the landscape. The field evaporation (E) leads to unproductive consumption of water, while transpiration (T) by the cultivated plants represents productive consumption. The percentages shown correspond to conditions in the semi-arid tropics in sub-Saharan Africa.[11]

Blue water consumption

Volumetric estimation and impact assessment of BW consumption has received detailed treatment in freshwater life-cycle assessment (LCA) literature including those studies dealing with the bioenergy-water nexus. Consumptive BW use is equal to the water withdrawal minus the portion of withdrawn water that returns back to water bodies where it is available for possible further use. Many estimates of consumptive BW use quantify consumptive water requirements of bioenergy, or thermoelectric systems, or other agricultural products.[12–14] Consumptive BW use is a relevant metric for analysis of freshwater consumption as a basis for quantifying impact on ecosystem and human health and well-being.[14]

Blue water withdrawal

Water withdrawal includes all (blue) water abstracted from a surface water body or groundwater aquifer for industrial, agricultural, or domestic usage. Withdrawal is contrasted against non-withdrawal water use, which includes in-stream use for such purposes as hydroelectric power generation, transport, fish production, and recreation. Non-withdrawal use is thus not directly relevant for agricultural use of water. Withdrawn water is either used consumptively and removed from the current hydrological cycle through evaporation, transpiration, or product incorporation; or it is released back to the environment (though maybe to a different water body or at different time) through recycling to water bodies, seepage, and runoff.

Most recent studies estimating the water requirements of biofuels focus on the consumptive use of water and do not estimate the withdrawal requirements.[13,15–19] The difference between withdrawal and consumption arises because of the spatial boundary selected for analysis. Water runoff from a farm due to irrigation system inefficiencies can be used productively in a downstream farm or it can contribute to environmental flow requirements in nearby rivers. Seepage losses from unlined irrigation canals can recharge groundwater or may have other environmental benefits. As an example, estimates of overall water use efficiencies for individual systems in the Nile Basin in Egypt are as low as 30%, but the overall efficiency for the entire Nile system in that country is estimated at 80%.[20] The concept is summarized by Perry *et al.*[21] who indicate that '…"losses" at the scale of an individual field or an irrigation project are not necessarily "losses" in the hydrological sense…' This has implications on how water intensity estimates are scaled up to total water requirements for production of biofuels at a regional or national level.

However, estimation of withdrawal and non-consumptive use of BW, essentially excess irrigation water, is also

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informative. Significant water withdrawals from surface water bodies may exert localized and/or seasonal impacts on the ecosystem as in the case of thermoelectric plants with once-through cooling systems. For regions dependent upon groundwater for irrigation, extraction of groundwater beyond recharge rates could lead to aquifer depletion.[22] As a result, estimation of water withdrawal intensity along with consumption intensity is also useful [23] and has been incorporated by some recent LCA literature.[24]

Green water consumption

GW consumption refers to crop evapotranspiration (ET_c) requirements met through precipitation. For rain-fed crops, demand for ET_c is met entirely through precipitation and soil moisture depletion (GW). Irrigation (blue) water is applied in regions where GW is insufficient to meet ET_c requirements.

Studies estimating consumptive water use differ in terms of whether and how to include GW. Ridoutt and Pfister [25] and Pfister *et al.*[14] argue that since GW processes occur also in the natural vegetation and are integrated with and conditioned to the land (in terms of geological, geographic, and hydrological processes) in the region under consideration, cultivation provides access to GW just as it does to solar radiation, wind, and soil. Therefore, they argue that GW use should be integrated with the land use category of LCA when quantifying its environmental impacts. In a similar vein, Milà i Canals *et al.*[26] recommend only estimating changes in BW formation due to land use changes when quantifying the environmental impacts associated with water consumption.

For understanding water flow dynamics, however, including GW in the analysis – as opposed to using it as an indicator for water use impact in LCA context – is critical in many cases: conversion of natural or managed vegetation to bioenergy feedstock plantations can alter interception of GW and affect BW formation (see the Jatropha case study). This change in hydrology can result in rising groundwater levels and increased river runoffs in some cases.[25,27–30] Changes in land use can also influence infiltration and runoff rates through influencing soil properties such as soil organic matter and vegetation cover over the year. Hoekstra *et al.*[31] favor estimation and explicit reporting of GW requirements, arguing that their inclusion acknowledges competing demands for limited freshwater resources. Water that is returned to the atmosphere through GW consumption may otherwise have replenished groundwater levels or contributed to river flows required for maintaining healthy aquatic ecosystems. Further, inclusion of GW provides a complete picture of water resource dynamics and is important for water resource management.[2,32] Accounting for GW may also help to better assess the effects on water resources in agricultural production in sub-humid and semi-arid regions, and facilitate developing strategies to tap the productivity of both GW and BW.[8,9]

Life-cycle water use

Literature from the LCA community tends to focus on the development of methods to quantify the impact of water consumption considering spatial differences in water scarcity and water use consequences on surrounding ecosystem.[14,26] To address the argument on system boundaries regarding whether to account for GW use, many new water life-cycle bioenergy studies combine all water use and explicitly state sources of water inputs throughout the lifecycle. Water inputs can include green and blue (surface and ground) water uses[24,25,33] as well as degradative[14] and grey water consumption.[3,34] Some studies also account for application losses[18,24] and conveyance losses.[24] Water that is lost to ET_c during biomass production for energy is not immediately available for food production or to meet environmental needs (until it returns as precipitation). Consequential LCA could find that shifting to bioenergy feedstock production could lead to increased/decreased ET and also affect other components of the water cycle as well as water quality. The net effects will depend on the character of both the reference system and the bioenergy feedstock production system put in place. In many instances, the effects of bioenergy production are best evaluated based on comparison to a reference system, which may be a natural system or alternative cultivation system in present time or in future business-as-usual (BAU) scenarios.

The production of bioenergy may generate coproducts that displace other products requiring water for their supply (e.g. animal feed crop). Conversely, the use of residue flows in forestry and agriculture for bioenergy does not lead to additional ET, although it may influence water resources and the environment in other ways (e.g. excess residue removal may increase erosion and reduce water retention capacity or, as when coproducts displace other products, indirectly influence ET if the residue is already used for other economic activities). In such cases the change in ET may take place in unspecified locations and with varying time delay.

Applications of metrics for water use assessment

The selection of assessment tools depends largely on the questions posed as well as their relevance to local/regional context. We select four case studies developed elsewhere[24,35–37] and summarized below to illustrate the importance of understanding the differences behind the various metrics and that different approaches are designed to serve different purposes. Following the order in Table 1, we introduce four case studies measuring BW consumption/withdrawal, GW consumption and crop water balance, and life-cycle water use at the farm, field, state, and global level. The selection of assessment tools depends largely on the questions asked as well as their relevance to local/regional context. For example, in regions where crops are mostly rain-fed, water withdrawal and BW consumption provide most direct ‘indicator’ of the impact of bioenergy production on local water allocation among various users (case study 1, sugarcane in Brazil). Despite the relevance of using BW as an ‘indicator’ for water use impact, using only BW in accounting the overall water budget fails to recognize the interactions between different components of water stocks and flows. Case study 2, Jatropha in India, illustrates that characterizing water budget at the field level, including GW flows, provides the appropriate accounting framework for identifying integrated soil, crop, and water management strategies to improve the productivity of bioenergy system without increasing local BW stress. The corn ethanol case study adopts the LCA approach and examines consumptive and non-consumptive GW and BW water use across the supply chain, as well as the displaced water use within or outside of the state boundary due to coproducts (case study 3, corn ethanol in the USA). Case study 4 (bioenergy feedstock, global assessment) compares the water necessary to produce and convert a given crop into a biofuel, providing a consistent inventory of water use assessment at the global scale.

Case study 1. Measuring BW withdrawal at the farm-system level and overall effects on stream flow[36]

Sugarcane cultivation in Brazil traditionally does not require irrigation. The practice of irrigation is more prevalent in the Brazilian north-east, which accounts for about 10% of total sugarcane production. While irrigation is becoming more common in the mid-west, it is still linked to supplementary or rescue irrigation either to restore soil moisture at field capacity or provide water needs during water stress periods. Irrigation volumes are low and range from 100 to 200 mm per year, and largely use nutrient-rich wastewater generated from industrial production of sugar and bioethanol instead of freshwater. Therefore the primary opportunity to reduce consumptive BW use in the sugarcane industry in Brazil lies in the reduction of water use at the mills.

Water withdrawal in the sugarcane industry was substantially reduced as a result of environmental legislation and by the gradual deployment of systems for recharging water resources, both of which followed the promulgation of the Brazilian Constitution in 1988. Water withdrawal was about 15–20 m^3/t cane around three decades ago due to the use of water open-circuits technology. Today withdrawal has been reduced to about 1.85 m^3/t cane through water recycling and other measures to improve the water use efficiency. Further improvements of wastewater treatment systems allowing increased reuse of water moves the sector towards the water withdrawal goal of 1.0 m^3/t cane.[36]

In the state of São Paulo – which has the largest concentration of ethanol and sugar mills in Brazil – water use by the sugarcane sector accounted for about 13% of statewide total water use and about 40% of the use by the entire industrial sector in 1990. Over the last two decades, the sugarcane industry in the state of São Paulo has increased its production greatly and at the same time reduced its relative water use, so that it now accounts for 25% of industrial sector use and 8% of total water use in the state, and projected to decline further to less than 1% of the state’s total water use by year 2015.[38]

Case study 2. Measuring the impact of land use changes on GW balances and BW formation[37]

Jatropha (Jatropha curcas L.), commonly known as purging nut or physic nut, is a perennial deciduous, multi-

Table 2. Annual water budget of Velchal village wasteland under two different land uses.[42]

	Fallow wasteland	Jatropha cultivated land with land management practices
Rainfall (mm)	896	896
Outflow from the watershed (mm)	393 (43%)	274 (31%)
E or ET (mm)	460 (52%) (Primarily non-productive++)	580 (64%) (High share productive use)
Groundwater recharge (mm)	43 (5%)	42 (5%)

++ Extensive grazing on wastelands results in that a small share of the total ET on wastelands is productive.

purpose shrub belonging to the family Euphorbiaceae. The decorticated seeds of this plant yield about 28–40% oil, which can be transesterified, blended with diesel and used as biodiesel. There is a need for breeding and genetic improvement of the species to achieve improved yield stability, and insect and pest resistance. Jatropha is a drought-tolerant wild plant with low nutrient demands, but little is known about its actual water requirements and production potential in different agro-ecological regions.[39,40]

It has been suggested that conversions of wastelands to biofuel cropping holds large potential for increased biofuel production and improved livelihoods in India.[41,42] The water balance for fallow wasteland and Jatropha cultivated land from a site located in Andhra Pradesh, southern India is presented in Table 2. The table partitions rainfall into three hydrological components: evapotranspiration from cultivated land (ET), runoff (outflow), and groundwater recharge. Share of rainfall lost as surface runoff from the watershed boundary reduced from 43% to 31% following cultivation of Jatropha in fallow wasteland. Correspondingly, water consumption increased from 52% to 64% of the total rainfall amount due to shift from soil evaporation to crop evapotranspiration, indicating that cultivation of Jatropha on wasteland could potentially utilize GW more effectively. Share of rainfall recharging groundwater remained constant in both scenarios.

In fallow wasteland, a large fraction of rainfall absorbed by the soil (in form of soil moisture) was being lost through soil evaporation in monsoon and non-monsoon periods. Diversion of water from runoff and evaporation to evapotranspiration led to increased plant growth. This benefited the landscape by increasing soil moisture content and reducing soil erosion and nutrient losses. Measured agronomical data shows that Jatropha produced approximately 1 to 1.5 tons of seed biomass ha^{-1} annually and biomass containing 1 t C ha^{-1} per annum was added in soil during dormancy (leaf fall and pruned plant parts). Thus, Jatropha could be a suitable candidate for sequestrating carbon and rehabilitating wasteland into productive lands over a long term time period.[42]

Volume and distribution of rainfall substantially affects crop yield. Higher but erratic rainfall in 2009 led to water logging and consequenty lower Jatropha yield compared to 2008. Contrary to the belief that Jatropha needs less water, this study indicates that Jatropha could use large amounts of water (1600 mm y^{-1}) under favorable soil moisture conditions for luxurious growth and high yield. Moreover, crop yield is found to be affected substantially by water stress. Integrating watershed development program together with improved germplasm may help in achieving economic crop yield of Jatropha plant in semi-arid tropics.[39,40,42]

Overall, changes arising from the conversion of wastelands into Jatropha plantations were desirable from an ecosystem's perspective at the watershed scale: groundwater recharge improved, non-productive soil evaporation was shifted to productive transpiration, and soil loss from the fields was reduced. At the sub-basin scale, reductions in runoff as a result of converting wastelands to biofuel plantations may pose problems for downstream ecosystems and water users if implemented on a large area; however, base flow actually improved with biofuel cropping while storm flows and sedimentation loads were lower. On the other hand, the risk from flooding and soil loss is reduced with lower runoff from the upstream land. The net impact of these changes depends on the characteristics of downstream water users and ecosystems.

Case study 3. Life-cycle water use for bioenergy from wastes and agricultural residue and 'avoided' water use due to coproduct[24]

Existing literature measuring water use by bioenergy do not account for coproducts from the process. For example, conversion of corn grain to ethanol also produces distiller's grain soluble (DGS) which is used as an animal feed. When DGS is used as animal feed it displaces other feed such as corn grain, urea and soybean meal (SBM), which in turn displaces raw soybean.[43,44] Thus the production of DGS precludes the need to produce such other animal feed and the displacement ratios can be used to calculate the amount of displaced products and the amount of water saved for not producing them. Similarly, using the lignin component of agricultural residues such as corn cob to generate electricity for the biofuel process and for export of surplus to the grid, displaces other electricity generation and associated water use. Figure 3 shows the estimated consumptive water intensity of grain and cob ethanol in the USA, as well as water credits allocated to co-products. It is interesting to observe that the study found: (i) coproduct credits are around 5% and 45% of total BW used to produce ethanol from rain-fed and irrigated corn, respectively, and around 50% of GW in both cases; the results reflect the lower yields and hence higher water intensity of soybean; (ii) the estimated low GW intensity of ethanol from corn grown in CA is resulted from the treatment of coproduct credits: the study assumed DGS produced in CA displaced high GW intensity soybean grown in the US Midwest.

The water effects of displacement illustrated needs to be interpreted with great caution, as the proposed approach in estimating water use may be different from the impact assessment in that the displaced water may be separated widely from the water effects of the ethanol production in both space and time. Deduction of the avoided water use due to coproducts from the total water use associated with ethanol production can therefore result in incorrect information about the local/regional effects. Evaluation of local impacts should consider the total water use from feedstock production, rather than the *net* water use after the consideration of coproducts.

Studies comparing water use of bioenergy and fossil fuel generally found that the total water requirements (GW+BW) of fuel production are higher for biomass than fossil fuel.[32] BW consumption of bioenergy from rain-fed crops and residue is generally lower than that of gasoline, but it is orders of magnitude higher if the bioenergy is from irrigated crops.[19,24] However, such comparison of volumetric water intensity of bioenergy and fossil fuels is simplistic. For example, cultivating rain-fed crops on marginal lands can in some cases reduce unproductive evaporation loss and increase water productivity and soil moisture level, and

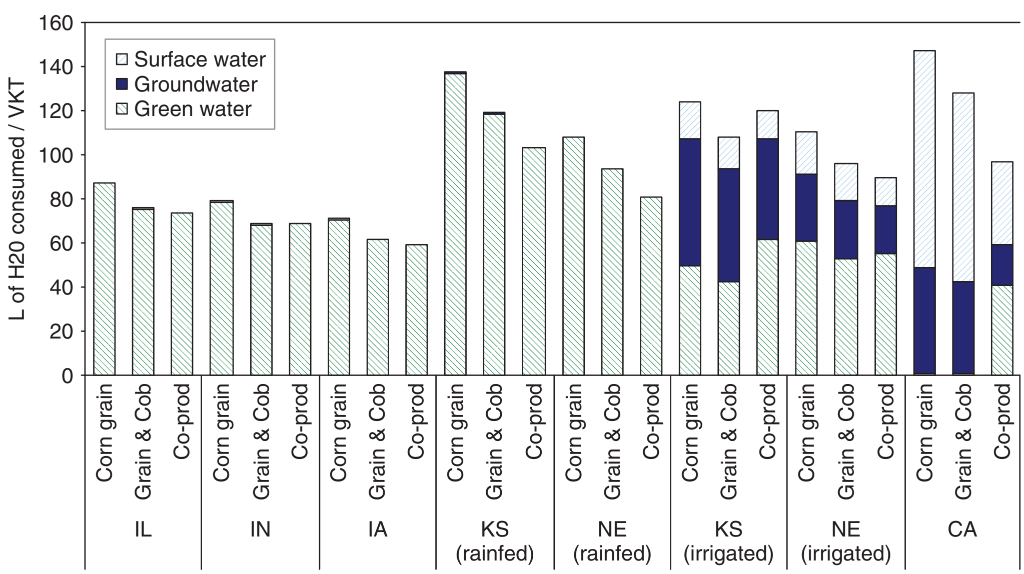

Figure 3. Water consumption intensity of ethanol from corn grain and crop residue, and the avoided/displaced water use credits assigned to coproducts – DGS and electricity.

  | *Biofuels, Bioprod. Bioref.* **5**:361–374 (2011); DOI: 10.1002/bbb

provide other sustainability benefits. On the other hand, as discussed earlier, the use of GW in some other areas can have impacts on terrestrial ecosystems and BW availability downstream. Though the water intensity of fossil fuels is on average low compared with biofuels, it has been widely reported that oil sands production and potential shale oil development could result in substantial stream water withdrawals and significant alteration of water flows during critical low river flow periods,[45,46] groundwater depletion and contamination, and waste water discharges.[47,48] A detailed comparison of bioenergy *vs* fossil fuel water use should carefully examine the impacts of water use on changes in water availability and quality and other ecosystem health effects at local and/or taking into account seasonable variations.

Case study 4. Global assessment of bioenergy feedstock water use[35]

Water scarcity can limit both intensification possibilities and the prospects for expansion of agriculture. Increased bioenergy demand presents both challenges and opportunities in this context and the outcome for the state of water depends on where and how (and obviously how much) bioenergy expands. Under strategies that focus on so-called first-generation biofuels for the transport sector, mainly using conventional agricultural food/feed crops as feedstock, the associated water use will resemble that driven by increasing food sector demand. However, the geographical pattern may be different since the demand for biofuels for transport may be differently distributed than the increasing demand in the food sector. International trade in biofuel feedstock and biofuels may also influence the geographical pattern of crop production and associated water use.

There is significant potential to increase the currently low productivity of rain-fed agriculture in large parts of the world through improved soil and water conservation including on-site water management.[49–51] Investment in agricultural research, development and deployment could produce a considerable increase in land and water productivity.[51–53] Ecosystem modeling can be used to assess the impacts of bioenergy expansion in relation to food production and water, but can also help improve the understanding of improvement potentials in agriculture and of the relative importance of different options for land and water management to improve the water productivity and land use efficiency.

The ecosystems modeling package LPJmL† was used to quantify water productivity for selected agricultural crops that are suitable as biofuel feedstock. The results in Fig 4 suggest that the water productivity varies considerably between the different crop-biofuel combinations and also that there is a significant geographic variation for same crop-biofuel combination. This underlines the importance of soil and climatic factors, but agronomic management is also a strong determinant of the water productivity by influencing the yield levels and relative importance of transpiration and soil evaporation. On a global basis, assuming that other resources than water are not limiting to growth, changing crop type to more water-efficient crops could theoretically increase energy outputs from biofuel crops by about 60% without impacting on runoff, i.e. leaving downstream users unaffected by this increase in output. Improved management could improve crop yields by 10–40%, depending on the degree of management improvements. The increased biomass production resulted in higher water consumption during growth, reducing runoff generation. However, this runoff reduction was found to be small in comparison with total runoff levels (below 1%).

Future directions

As illustrated in this perspective, metrics measuring various categories of water use provide useful tools for water resource management and planning at local, regional, and global scales. Accounting for GW consumption and BW withdrawal and consumption across product life-cycles, enable us to better understand the total water demand within certain time frames and spatial boundaries. These assessments also enable us to measure the efficiency of the agricultural and bioenergy production systems, and to identify the potential management strategies or feedstock varieties to optimize water use at the plant, farm, regional, and global scale.

† LPJ is a dynamic global simulation model of vegetation biogeography and vegetation/soil biogeochemistry. Taking climate, soil and atmospheric information as input, it dynamically computes spatially explicit transient vegetation composition in terms of plant functional groups, and their associated carbon and water budgets. LPJmL (mL for managed lands) additionally simulates the carbon and water budgets of agricultural lands and of land use change. It takes as inputs land use and land management data.

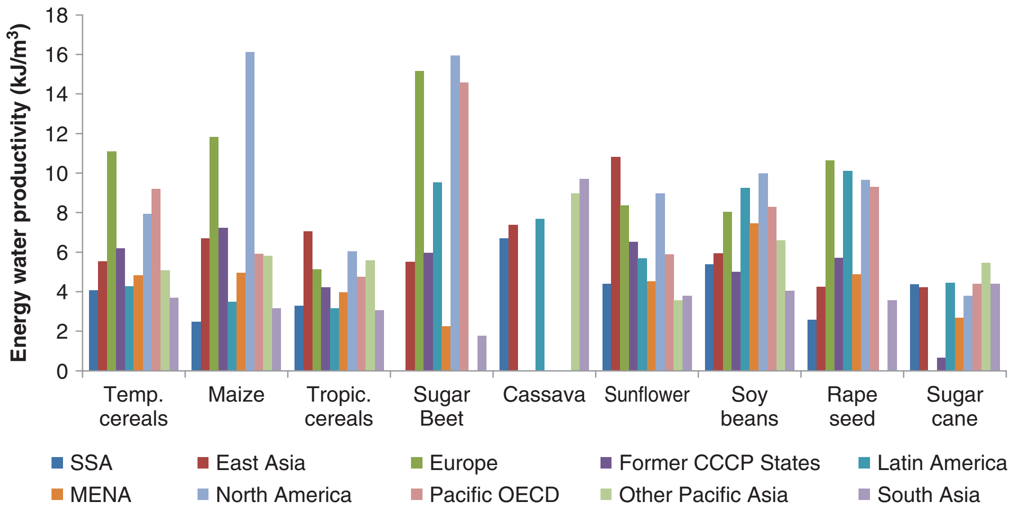

Figure 4. Biofuel produced per unit water consumed for selected agricultural crops. Average of national bioenergy water productivities without any weighting for country sizes. The modeled data correspond to average values for the simulation period 1998–2003.

However, a careful translation is needed from the water use assessment to impact evaluation. Water use evaluation oftentimes employs, by necessity, *spatial* and *temporal* aggregation that sums more than one form of water consumption (blue, green, and gray water), in locations where the relative importance of water-related aspects differs. Thus it often carries no clear indication of potential social and/or environmental harm or tradeoffs.[14,54] Similarly, *temporal* aggregation over an annual period ignores the inter-seasonal variability of water use and water scarcity (which are often substantial in certain regions) and therefore may not convey the important information about seasonal water use competition or excess unless this simplification is clearly spelled out. Recent literature on freshwater LCA has developed regionally differentiated characterization factors that measure water scarcity at a water basin level or even higher resolution[26] and also account for temporal variability in water availability.[14] Volumetric estimates of GW and BW can be converted to characterization factors, providing a 'stress-weighted' or 'ecosystem-equivalent' water use estimate that can be compared across regions. Work is ongoing to use the explicit water use results to undertake impact analysis and accurately assess the effects of biofuel production on water resources. These will be discussed in greater detail elsewhere in this special issue. Figure 5 summarizes the water flows, indicators introduced in this perspective and effects that link to different levels of protection.

In addition, water use indicators may not always convey the most salient information if they fail to include other critical information regarding land use and the current and future reference systems. For instance, production systems having lower yield levels may be preferred in water-scarce areas since high yield systems might reduce downstream water availability for ecosystem and human uses, necessitating balance between upstream benefits and downstream costs. So water use indicators when combined with land use indicators and a treatment of baseline versus counterfactual scenarios provides a more accurate assessment of changes in water resource allocation and impacts in a specific region.[57]

On the local/regional level, the critical question to address is how a shift to the bioenergy system influences the character and intensity of water use. Local/regional conditions determine what water aspects – and hence water use indicators – are most relevant to consider and also the relative importance of water aspects compared to other aspects such as effects on soil quality or biodiversity. It is also important to compare bioenergy options with possible alternative land use options; the bioenergy option can cause both positive and negative effects and these must be weighted and compared with the effects of the alternative land use. Crops with the same or higher water productivity could have beneficial effects if the annual ET is redistributed over seasons with

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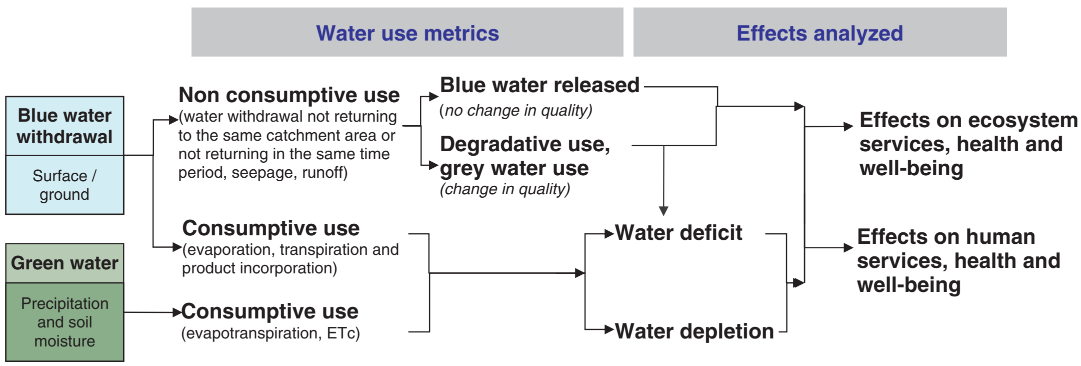

Figure 5. Different types of water use characterized in water LCA studies and resulting effects measured by various indicators.[14,26,55,56]

little water shortage problem, resulting in reduction in irrigation volume or in other adverse impacts on soil moisture and seasonal water flow.[58] Non-productive evaporation can be replaced by productive evapotranspiration by careful selection of biofuel crops in arid regions, leading to further increase in GW consumptive use without exacerbating runoff and groundwater recharge.

Ultimately, the land use choice will be determined by land users' prioritization of bioenergy products versus other products obtained from land – notably food, fodder, fiber, and conventional forest products such as saw wood and paper – which will be determined by the (positive and negative) environmental, social, and economic consequences associated with the different types of production. This in turn depends on natural conditions (climate, soils, topography) and on agronomic and forestry practices in producing the biomass, but also on how societies understand and prioritize water related aspects *vs* other aspects such as nature conservation and soil/biodiversity protection. All these important considerations will affect how the production systems are shaped to reflect these priorities.

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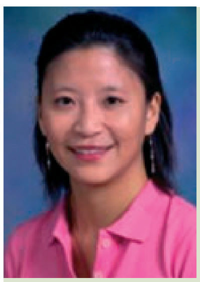

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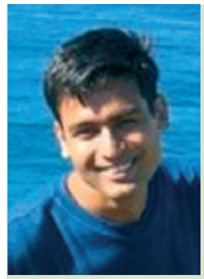

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