Perspective

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The bioenergy and water nexus

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Abstract: Promotion of energy from biomass for reducing greenhouse gas emissions has led to increased usage of freshwater, especially during the cultivation of biomass. This has raised concerns about the increase in water stress, particularly in countries that are already facing water shortages. Attempts are being made to characterize the effect of water demand induced *inter alia* by increased bioenergy usage. Also, alternatives are being developed to mitigate such impacts by improved management so that bioenergy can be beneficially utilized. Future studies on bioenergy will need to take into consideration the water aspect so that the trade-offs between climate change mitigation and water stress are addressed. © 2011 Society of Chemical Industry and John Wiley & Sons, Ltd

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Introduction

Freshwater is already scarce in some regions of the world and under the impact of population growth and climate change, the population at risk of water stress could increase substantially (water stress index at the watershed level is presented in Fig. 1[1]). Estimates show that in 2005, about 35% of the world population lived in areas with chronic water shortage.[2] Water shortages are already beginning to constrain economic growth in several places in the world, including California, China, Australia, and India.[3] *The Global Environmental Outlook* estimates that by 2025, two-thirds of the global population will be living in areas experiencing water stress, i.e. where periodic or limited water shortages can be expected.[4] Agriculture accounts for about 70% of freshwater withdrawals from rivers, lakes, and aquifers – up to more than 90% in some developing countries.[3]

At the same time, a growing population and changing dietary trends, rapid urbanization and a fast-growing demand for most resources mean a sharply rising demand for forestry and agricultural products.[5] A corresponding increase in the demand for biomass results in growing pressure on forestry and agriculture to increase their production both through the adoption of more intensive and efficient practices, but also through expansion in the land used to produce biomass. The concerns over climate change and energy security import dependency have led to the situation where many countries promote the use of solid, liquid, and gaseous biofuels for heat and power as well as for transport.

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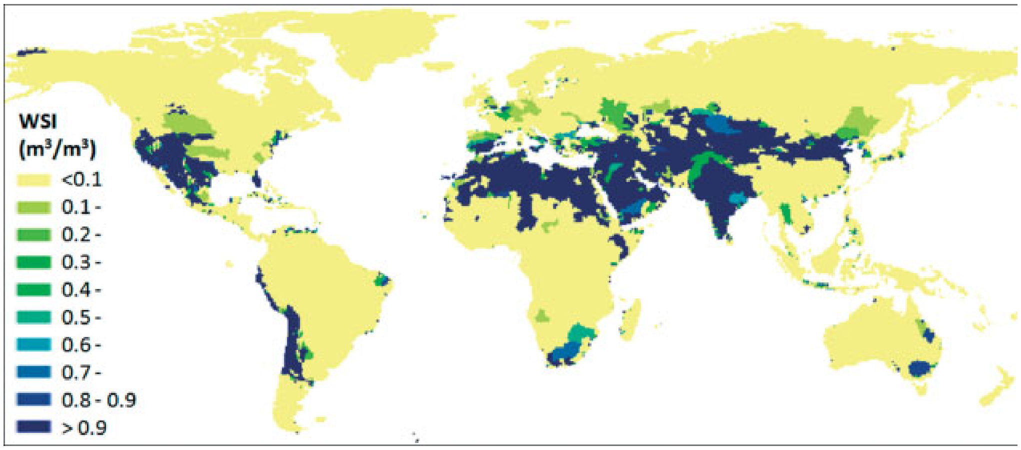

Figure 1. Characterization of water stress index at the watershed level per m^3 water consumed.[1]

Bioenergy is also promoted in many places because it is considered a possibility for job creation and improvements in livelihood conditions, especially in rural areas.

In recent years, the link between bioenergy and water has received increased attention, but historically, availability of suitable land has been the primary focus when the potential of bioenergy has been studied.[6,7] These studies have arrived at different conclusions about the future bioenergy potential but many of them conclude that it should be possible to produce several hundred EJ of biomass for energy some decades into the future. This can be compared with today's global industrial roundwood production corresponding to 15–20 EJ/yr, and the global harvest of the major crops (cereals, oil crops, sugar crops, roots and tubers, and pulses) corresponding to about 60 EJ/yr. Clearly, biomass extraction in agriculture and forestry will have to increase substantially and both land-use intensification and expansion of managed land may be needed in order to realize such potentials. Noting that agriculture is already the biggest water user consuming approximately 70–80% of global freshwater supplies,[3] it is clear that the future state of water resources may be influenced by the strategies established for bioenergy expansion and vice versa.[8,9]

Visions of how the growing bioenergy demand can become a driver of both sustainable rural development and sustainable land use commonly propose that establishment of bioenergy plantations can help making productive use of abandoned agriculture land and restore degraded soils.[10,11] Studies primarily point to potential benefits such as avoided land-use change emissions (or soil carbon sequestration in soils and biomass), increased soil productivity, and water quality improvements.[12] They have so far paid limited attention to water as a limiting factor, even though studies have clearly documented the importance of land-use change on the state of water resources[13] – also showing that forestation or other land-use changes that increase evapotranspiration rates can significantly influence local hydrological cycles, including reducing stream flows and downstream water.[14–16]

A widely debated issue in recent times relates to the competitive situation between the production of food, fiber, and biofuel.[17,18] The nature of the links between increased bioenergy production and rising food and fiber prices is disputed, but we are still justified in asking: 'What consequences might an expansion of bioenergy production have regarding the use of land, water and other resources including biodiversity and the sustainability of other ecosystems?'

The bioenergy-water nexus

Water is often *implicitly considered* in conventional bioenergy potential studies since the amount of precipitation and soil-water characteristics are two of the parameters determining suitability for bioenergy production. But the studies provide little insight into local and regional water consequences of actually realizing the assessed bioenergy potentials by shifting land use to provide biomass for energy. It is of utmost importance for the future state of the freshwater resource how – and where – biomass is produced for energy.

As water has become acknowledged as a key issue in relation to bioenergy development (and land use in general), various indicators and assessment tools have been proposed to include the water perspective in analyses and to assist strategy development and land-use planning. Ideally, such indicators and tools should not only help in hedging against risks and undesired development but also in identifying opportunities and synergies in relation to water management. If done right, careful integration of bioenergy into the agriculture/forest landscape could optimize the utilization of water and also mitigate water quality impacts associated with the present land use. However, if done poorly, biomass production may create new problems and exacerbate already unsustainable uses of land and water.

The largest component of water use associated with bioenergy production is from the cultivation of the biomass feedstock.[6,19–23] Depending on the location, agricultural practices, and growing period of the crop, the source of this water may either be rainwater or surface and groundwater that is used to supplement rainfall through irrigation. In addition, the pollution of water through the use of agrochemicals may be characterized indirectly as a 'water use' as it can result in the reduction of freshwater usability due to contamination of water resources. These aspects of water use are the same for bioenergy and agriculture in general, whether for food, fiber, or fuel. However, feedstock production for bioenergy may increase the competition with food and fiber for a limited resource, viz. water. From a life cycle perspective, in addition to the direct water use associated with the biomass production, the 'embedded' water in agrochemicals during their production as well as water used in the post-harvest processing of the feedstock for producing the appropriate energy carrier (e.g. pellets, wood chips, bioethanol, and biodiesel) must also be considered. Furthermore, bioenergy strategies often emphasize high land-use efficiency (i.e. maximize bioenergy output per unit land), one reason being that this can mitigate the risk for (direct and indirect) land-use change emissions. This focus on land use efficiency may lead to a preference for high-yielding systems employing large inputs of fertilizers, pesticides, and irrigation water. Such bioenergy systems may place a large demand on local water resources and also increase the pollution load from fertilizer and pesticide leakage – thus, in some places there might be trade-offs to manage between climate change mitigation and water.[24]

From a methodology point of view, there are two ways of approaching the bioenergy-water nexus: (i) product-oriented approaches that evaluate the environmental effects of alternative ways of meeting consumption needs; and (ii) approaches that have a watershed focus and evaluate the consequences of land use on catchment water yield and environmental flow requirements. As further discussed later, 'water use' can be defined differently depending on scope and purpose of studies and whether a product-oriented approach or a watershed approach is used.

Types and scales of analysis

Temporal and spatial scales of analysis

Expansion of dedicated biomass for energy, especially the establishment of large-scale bioenergy plantations, on sparsely vegetated areas, might increase evapotranspiration leading to diversion of water from runoff to surface water as well as reduced recharge of groundwater.[25,26] On the other hand, if bioenergy plantations are located in the landscape so as to reduce runoff, this may result in lower soil erosion at the site as well as reduced risk of flooding and reduced sedimentation in rivers, clearly a positive effect. To reduce the non-productive component of evapotranspiration, methods such as rainwater harvesting and improved soil and land management have been proposed.[26,27] This could lead to increased plant productivity with reduced effects on freshwater in rivers, lakes, and aquifers. However, characterization at different spatial and temporal scales of the water use for bioenergy production – and of associated water-related consequences – is necessary if the effects are to be understood and options developed for minimizing negative effects and optimizing positive opportunities. Key points to note when considering the interaction between water resources and bioenergy production are:

1. The interaction between land use associated with bioenergy production and water resources varies in time and space.
2. Water not only moves vertically (evaporation and transpiration), but also laterally through hill slopes, soils, groundwater, and rivers; hence, any influence on water quantity or quality can be transmitted through a catchment and have a significant impact downstream.

Outside of the basin, water also moves virtually through space and time due to the trade of agricultural commodities.

3. Thresholds may exist beyond which far-reaching consequences can occur – including complete ecosystem transition to new states, which may appear to take place rapidly when thresholds are crossed and where a return to the previous ecosystem state can be difficult.

Natural systems consist of complex webs of linearly and non-linearly interlinked subsystems. Sustaining them requires consideration of this complexity and the underlying uncertainties. This presents considerable challenges in relation to the development of guiding principles, criteria, and indicators required by actors engaged in activities (including planning and policy-making) that directly or indirectly influence the state of natural resources including soil, water, and ecosystem health in general. Many order-of-magnitude-type indicators, based on volumetric aggregation of water use, have been found inadequate in this regard.[28]

In the context of bioenergy, different evaluation frameworks, criteria, and indicators have been proposed. The so-called 'water footprint' (referred to as 'virtual water footprint' here to avoid confusion with life-cycle-assessment-based approaches described later) builds on the concepts of green water and blue water[29] i.e. (i) green water, which is rainwater available in the root zone that flows due to evaporation and plant transpiration; (ii) blue water, which is the surface and groundwater used for irrigation or other (industrial or residential water supply) purposes. A third component, gray water, representing the water required to dilute the pollutant emissions to reach defined water quality requirements, is added and a single index – the virtual water footprint – can be obtained based on combining the three components.[30] The virtual water footprint representation has received significant popular media attention as being an effective communication tool. But because it reduces complexity to a single value based on average spatial and temporal conditions, it has also been criticized as lacking consideration of (strongly varying) local water contexts, i.e. impact, including temporal and spatial variation of water resource availability and competing use, and the risk that laymen do not understand the differences between the different types of water use,[31] i.e. it discards too much detail to retain conceptual clarity and scientific rigor. Attempts have been made to modify this concept by separating the water use by source and by using regionalized water stress indices to make a more meaningful presentation of the water use.[32] In environments where water scarcity is a concern, approaches to assessing the impact of land-use change, such as afforestation, have been far more sophisticated. For example, in both South Africa[33–35] and Australia[36] comprehensive methods to assess the impacts of land-use change on water resources and environmental flows have been developed.[37] In the case of South Africa, these have been written into law, i.e. the establishment of commercial forest plantations is termed a 'streamflow reduction activity' and requires a water-use license.

Based on the reasoning that water use and losses in essence are merely transfers within the broader hydrosphere, water engineering approaches that have been developed utilize water balances, i.e. inputs and outputs given a defined system, to identify and quantify all water flows so as to estimate the water use.[38] Depending on how the studied system is defined, such approaches may or may not allow consideration of effects over varying spatial and temporal scales. Too narrow system boundaries may lead to downstream consequences being missed and these kinds of studies may also leave out water quality aspects and therefore fail to consider the reality that water may become degraded beyond the point of critical pollution – limiting further use to those that can make use of such degraded water, or requiring additional water for dilution to meet quality requirements for other uses.

Life cycle assessment approach

Water is also increasingly considered in life cycle assessment (LCA) studies, where methods are developing over time, for instance in the context of standards (ISO 14040/44) providing principles and guidelines for LCA. Earlier, water was coarsely aggregated as a volume over the entire life cycle of a product, the only distinction being made qualitatively regarding the source without further consideration of whether the water was used from limited resources in dry areas, or from abundant and renewable resources in wet areas. There was no attempt at modeling the impact pathway unlike for other impact categories.

However, more recently the desire to characterize water at a more refined level has motivated significant activities both at the inventory and impact assessment stages.[1,39,40] Further development of water accounting in LCA is presently taking place, examples being the initiatives from the World Business Council on Sustainable Development (WBCSD) and the UNEP.SETAC Life Cycle Initiative.[39] The UNEP. SETAC Life Cycle Initiative provides a framework for assessing consequences of freshwater consumption and shows possible impact pathways with regard to human health, ecosystems, and resources. The framework proposes parameters that should be taken into account when establishing characterization models for describing these impact pathways on the midpoint and endpoint levels. It recommends that the assessment method should be regionalized in reference to the hydrological context. Freshwater consumption is here recognized as a phenomenon that can create impacts on human health, ecosystems, and resources by lowering groundwater levels and in other ways reducing water availability for meeting other needs, including maintenance of ecosystem function and diversity. Consequences of water consumption (e.g. resource depletion, human health, and reduction in biodiversity) can be modeled at the midpoint level and at the endpoint level.[39] In response to the controversies and inconsistencies around the different water footprinting approaches, the International Organization for Standardization (ISO) is considering the development of a new standard to establish a set of internationally harmonized metrics for water footprints. Now at the stage of Preliminary Work Item (PWI), ISO 14046, *Water footprint – Requirements and Guidelines*, is intended to complement existing standards on LCA and ongoing work on carbon footprint metrics.

Since LCAs typically consider multiple impacts, they may sometimes include weighting of different impact categories, which enable the trade-offs between water-use impacts and other environmental impacts or positive aspects to be quantitatively compared. However, it needs to be noted that the weighting to make various environmental impacts mutually comparable is controversial – not least since value judgments are inescapable.

Attempts are being made to integrate local and regional conditions within the impact assessment scheme – including water quality, water availability, the socio-economy, and water allocation requirements. These assessments can be made at watershed level, national level, or across these levels depending on the scope and conditions. Temporal variations (e.g. seasonality) are also important for assessing water stress and thus should be included in future modeling efforts.

Future developments

Presently, the most common use of biomass for bioenergy is through the traditional use of charcoal, wood, and manure for cooking, space heating, and lighting generally by poorer populations in developing countries. Modern bioenergy use for industry, power generation, heat, or transport corresponds to about 20% of total bioenergy, but this share is growing rapidly. While wood and other lignocellulosic biomass are mostly used for heat and electricity generation, biofuels for transport presently use conventional food/feed crops as feedstock. But there is significant research and demonstration of technologies for converting lignocellulosic material into various types of so-called second-generation biofuels, such as alcohols, diesel substitutes, and methane.[41] It is likely that within the next ten years, conversion of lignocelluloses to biofuels will have reached a stage that these become the primary and preferred feedstock for biofuel production, in particular bioethanol. When such technologies become commercially available, there may be a shift in the preferred biofuel feedstock types, where the presently used conventional food crops (sugar and starch crops and oilseeds for the so-called first-generation biofuels) are replaced by lignocellulosic feedstocks, such as dedicated, high-yielding lignocellulosic plants grown in both short and long rotations as well as agriculture and forestry residues. Such a shift will significantly change the way biofuel feedstock production affects the water resource.

In the first instance, it is likely that growers who have bought into the production of first-generation crops will start to consider the relative value of their residues. In particular, crop residues may in the future form part of the biofuel feedstock in the same way as residues and processing by-flows in food and forest sectors are today used to produce solid biofuels. This is especially crucial for conventional (first-generation) biofuels where the 'main' product represents only a fraction of the actual biomass produced.[42] The use of residues and processing by-flows could reduce the water intensity of bioenergy substantially since the water that is used to produce the food and conventional forest products is the same that will also produce the residues and by-flows used for bioenergy. The water productivity can also increase as more utility (e.g. both food and bioenergy) is obtained per unit water used.

However, hydrologically, the role of residues is well known and reported extensively through the conservation agriculture and related literature[27] – in particular, the increased soil moisture storage resulting from increased infiltration and reduced evaporation associated with a good mulch cover. Thus increased biomass extraction can lead to decreased soil moisture storage with the consequence that less water is available to a plant and more is lost to soil evaporation – and possibly also to runoff where erosion impacts of more intensive runoff may increase. Furthermore, the role of residues as an important aspect of soil health and its role in carbon sequestration in soils must be considered. The effects of increased residues use for bioenergy on local/regional hydrology depends on site-specific conditions as well as the specific residue extraction rates: studies of the value of crop residues such as green fertilizers and mulch relative to the value of that residue as a bioenergy feedstock are clearly warranted.

Furthermore, considering the possibility that large areas of high-yielding lignocellulosic plantations could become established as a consequence of growing bioenergy demand, hydrologic effects of such land-use changes need to be studied. For instance, the use of marginal areas with sparse vegetation for establishing high-yielding bioenergy plantations may lead to substantial reductions in downstream water availability. This may become an unwelcome effect in water-scarce areas requiring management of a trade-off between upstream benefits and downstream costs. In other places, such as in parts of Australia where lands are affected by dryland salinity, increased evapotranspiration is already part of some land management strategies since it can help in addressing soil salinity problems.[36,43]

In addition, the plans for large-scale bioenergy production need to be discussed while considering the possible effects of climate change on the hydrological cycle. One of the key issues with water resources is that the spatial and temporal variations of impacts on water resources are predicted to be accentuated due to the effect of climate change. Climate change may alter the frequency, intensity, and duration of precipitation events affecting water supply. Changes in runoff are expected to reduce water availability in rivers and aquifers. Effects on water quality and increase in seasonal water demand for crops are also anticipated.[3] In this context, growing bioenergy demand also presents opportunities for adaptation to difficult water situations and promotion of more sustainable water management. For instance, some bioenergy crops are drought-tolerant and relatively water efficient and can be grown in areas not suitable for conventional food and feed crops. Some can be cultivated as vegetation filters for treatment of nutrient-bearing water (e.g. pre-treated wastewater from households and runoff from farmlands). Soil-covering plants and vegetation strips can be located to limit water erosion, reduce evaporating surface runoff, trap sediment, enhance infiltration, and reduce the risks of shallow landslides.[26] Thus, there is an urgent need to study the hydrologic effects of different types of bioenergy systems (at local, regional as well as global levels), to better understand how bioenergy expansion may influence the state of water resources.

Conclusion

The current expansion of bioenergy with a view to both mitigate climate change and provide more sustainable energy solutions portends to have significant implications on land and water use. Increases in demand for freshwater may exacerbate the already existing water stress, which, in some regions, is further expected to be compounded due to the effects of climate change. However, the effects of increased biomass production on water resources may be ameliorated through proper land, water, and agricultural management practices. To characterize the impacts on water resources, various criteria and indicators under different frameworks are being developed; virtual water footprint and LCA being two such examples. For a meaningful evaluation, all the frameworks need to take into consideration the distribution of freshwater sources as well as the temporal and spatial scales (local, regional, watershed, etc.) at which impacts may occur. Evaluation of impacts on water resources will be an important component of any assessment of energy from biomass in the future.

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