Biofuels and Water

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Introduction

Energy and agricultural water use are linked in synergic and conflicting ways (Hellegers et al. 2008). Large amounts of energy are consumed to pump groundwater to irrigate crops. Multipurpose dams combining power generation and irrigation often justify investments that may not have been economically feasible for one purpose alone. At the same time, conflicts may arise over water allocation between hydropower and irrigation. Higher demand for energy derived from biomass increases water demand and changes water resource allocation.

The cultivation of crops and biomass for food, fiber, or energy requires vast amounts of water (Molden et al. 2007a). Though, at present, the contribution of energy crops in overall agricultural water demand is modest, this may rise as rising energy prices, geopolitics, and concerns over the impacts of greenhouse gas emissions drive increased biofuel production. This potentially leads to more intensive competition between food and biofuel for land and water resources, particularly in already water-scarce areas. Thus, with growing food demand and increasing claims on water resources from other sectors, agricultural water management must improve.

A recently completed assessment on water management in agriculture (CA 2007) concluded that there are sufficient land and water resources to feed the world, but that today's food production and environmental trends, if continued, will lead to water crises in many parts of the world. Other projections on future water also foresee a worsening of water problems unless adequate policy measures are implemented (Seckler et al. 1998; Rosegrant et al. 2002; Alcamo et al. 2005; Vörösmarty et al. 2005, Lobell et al. 2008). Yet, none of these studies included the production of large-scale energy crops as a new source of water demand (Berndes

De Fraiture, C. And G. Berndes. 2009. Biofuels and water. Pages 139-153 in R.W. Howarth and S. Bringezu (eds.) Biofuels: Environmental Consequences and Interactions with Changing Land Use. Proceedings of the Scientific Committee on Problems of the Environment (SCOPE) International Biofuels Project Rapid Assessment, 22-25 September 2008, Gummersbach Germany. Cornell University, Ithaca NY, USA. (http://cip.cornell.edu/biofuels/)

2002). This raises questions as to whether water resources are sufficient to meet future demands for the production of food, feed and biofuel, and what the impact of increased biofuel demand on already stressed water resources will be (Varis 2007; National Academy of Sciences 2008).

This chapter provides an overview of water needs for food and biofuel systems now, including for growing crops and for processing. We then describe the water implications of some possible future biofuel systems, including prospective water productivity improvements and the use of alternative (less-water-demanding) crops. Finally, we explore possible impacts of increased water demands on other ecosystem services and possible mitigation measures.

The context: Water for food

To meet global food and fiber demand, crops evaporate between 6,800 km^3 and 7,130 km^3 of water annually (Postel 1998; Rockstrom et al. 1999; Molden et al. 2007b). This is equivalent to more than 3,000 liters per person per day, an order of magnitude larger than the combined quantity needed for drinking (2-5 liters) and for domestic purposes (20-300 liters). Water needed to grow crops comes from rain falling on agricultural lands, supplemented by irrigation where needed. Most of the crop water requirements, some 80%, are met directly by rainfall. For the remaining 20%, some 2,650 km^3 of water are withdrawn from rivers and lakes, accounting for 70% of all water diversions for human purposes. Some regions rely heavily on irrigation (e.g. North Africa, South Asia, and North China Plains); while in other regions, agriculture is mainly under rainfed conditions (e.g. Latin America, Europe). With increasing urbanization, domestic and industrial water needs are expected to rise faster than agricultural water demand, but according to most projections, agriculture will remain the largest user by far.

As incomes rise, food habits change in favor of more nutritious and more diversified diets. Generally, this leads to a shift in consumption patterns among cereal crops and away from cereals towards livestock products and high-value crops such as fruits, vegetables, edible oils and sugar (Rosegrant et al. 2002; Bruinsma 2003; Pingali 2004). Cereal demand projections range from 2,800 to 3,200 million tons (Mt) by 2050, an increase of 55% to 80% from current levels, largely to feed livestock. Meat demand projections vary between 375 and 570 Mt by 2050, an increase of 70–155% from current levels. Sugar, oil, vegetable, and fruit demands are also projected to increase substantially. The changes in diet have important implications for agricultural water use. Livestock products and the production of sugar and oil typically require more water per unit output than staple grains. Without improvements in productivity, crop water requirements may increase as much as 70 to 110% by 2050 (de Fraiture et al. 2007). In semi-arid and semi-humid areas, where most of the population growth is expected, an increasing part of the crop water requirements will likely be met by full or supplementary irrigation.

Already there are signs of growing water scarcity, particularly in some important agricultural areas in the world. For example, declining water tables are evident in the western USA, North India, Pakistan, North China, Mexico, and the Mediterranean, among others (Shah et al. 2007), and numerous rivers around the world (e.g. Yellow River, China; Krishna River, India; Syr Darya River, Central Asia; Colorado River, western USA; and Murray-Darling River,

		ET $^+$ in m^3/GJ Berndes 2002 *		ET $^+$ in m^3/GJ WWF 2006 **	
Feedstock	**Fuel**	**Low**	**High**	**Low**	**High**
Rapeseed	Biodiesel	100	175		
Oil palm	Biodiesel			46	250
Soybean	Biodiesel			143	500
Sugarcane	Ethanol	37	155	18	35
Sugar beet	Ethanol	71	188	48	76
Corn	Ethanol	73	346	100	323
Wheat	Ethanol	40	351	143	500
Sweet sorghum	Ethanol			56	233
Lignocellulosic crops	Ethanol	11	171		
Lignocellulosic crops	Methanol	10	137		
Lignocellulosic crops	Hydrogen	10	124		
Lignocellulosic crops	Electricity	13	195		

Table 8.1 Water requirements of different types of biofuel feedstock per unit of energy produced.
+ ET = evapotranspiration
* Estimates by Berndes 2002 include liquid fuel, heat and power; the lower range numbers include systems that deliver both biofuels for transport and heat/electricity.
** The WWF estimates the energy content per crop without specifying the energy carrier.

Australia) no longer discharge to the sea for extended periods of time (Molle et al. 2007). Climatic change may aggravate water shortages in these areas.

Water needs for biofuels now

The water requirements of energy derived from biomass are about 70 to 400 times more than that of other energy carriers such as fossil fuels, wind, and solar (Gerben-Leenes et al. 2008). More than 90% of the water needed is used in the production of the feedstock. A relatively small amount is used in the processing of biomass (Berndes 2002). Evapotrans-piration (ET) rates for different types of biomass per unit of energy are presented in Table 8.1. For comparison, Gerbens-Leenes et al. (2008) estimate the averaged water requirements for fossil energy at ~ 1 cubic meter ET per gigajoule of energy (m^3 GJ^{-1}) compared to 24 - 146 m^3 GJ^{-1} reported for bio-energy. Biodiesel and ethanol derived from conventional food crops typically require more water than biofuels based on lignocellulosic crops, but there is a wide range indicated for all alternative feedstocks (Table 8.1) and locations where the crops are grown (Table 8.2).

The wide range of water requirements presented are explained by the following:

- the water productivity of the crop depending on crop type, variety, soil, climate, day length and agronomic practices
- the variation in share of aboveground biomass usable as feedstock
- differences in conversion efficiencies of technology and options for co-production of electricity/ fuels which increase the bio-energy output per unit water input.

In some areas, energy crops are fully rainfed and in others, most of the water needs are met by irrigation (Table 8.3). Sugar beet is found in the temperate zone and is cultivated under rainfed conditions or supplementary irrigation (USA). In Brazil – the largest sugarcane producer – rainfed cultivation dominates, with irrigation used only in the most critical periods in the Center-West region and somewhat more frequently in the Northeast region (primarily salvages irrigation at planting and supplementary irrigation in periods of most critical growth). In India – the second largest sugarcane producer – sugarcane is mainly grown under full control irrigation. Maize is mostly irrigated in China, but only partly so in USA (China and USA are main producers). Palm oil and cassava are typically grown under rainfed conditions. (Muller et al 2008). In Europe crops for biodiesel (rapeseed) are also largely rainfed. A liter of ethanol, based on irrigated sugarcane in India, requires 3,500 liters of irrigation water; the same liter produced from irrigated corn in China needs 2,400 liters of irrigation.

While feedstock processing requires much less water than what is lost in ET during cultivation, this water is primarily extracted from lakes and rivers. Withdrawals range from just a few to about ten liters of water per liter biofuel, depending on process design (Berndes 2002; Keeney and Muller 2006). Thus, the impact from feedstock processing on water resource consumption is substantially less than that incurred in the agricultural phase; rather biomass processing has greater negative impacts due to potential chemical and thermal pollution loading to aquatic systems from refinery effluents and fate of waste or co-products. Solutions are available for mitigating the environmental impacts which result from biofuel plants, but may not be installed in regions with lax environmental regulations or limited law enforcement capacity.

At present, the total water requirement of transport biodiesel and bioethanol, made of food crops (sugarcane, maize, and rapeseed), is modest compared to that of food production. We estimate that biofuel crops account for an additional 100 km^3 annually (i.e. about 1.4% of total food crop ET). In

Table 8.2 Comparison of different feedstock crops in selected countries.

[a] Fraiture et al. 2008; includes the liquid fuel only.

[b] Gerbens-Leenes et al. 2008: estimates the energy content of the crops.

Country	**Main crop**	**ET m^3/ GJ [a]**	**ET m^3/GJ [b]**	**Irrigation m^3/GJ [a]**
Brazil	Sugarcane	152	25	4
USA	Maize	87	18	21
Canada	Wheat	232	--	17
Germany	Wheat	67	--	0
France	Sugar beet	54	--	0
Spain	Wheat	220	--	0
UK	Sugar beet	54	--	0
Netherlands	Rapeseed	--	67	
China	Maize	197	--	129
India	Sugarcane	229	--	278
Zimbabwe	Sugarcane	--	31	
Global Avg.		104		41

Table 8.3 Major crops used for the production of biofuels, main producing countries and the share of area under irrigation for the year 2000 (Source: Muller et al. 2008).

Crop	Main producing countries (both food and fuel)	Land under irrigation (%)
Sugarcane	Brazil/ India/ China/ Thailand	14 / 80 / 28 / 64
Sugar beet	France/ USA/ Germany/ Russia	15 /53 /5 / 5
Cassava	Nigeria/ Brazil/ Thailand/ Indonesia	0
Maize	USA/ China/ Brazil/ Mexico	21 / 40 / 0 / 17
Oil palm	Malaysia/ Indonesia/ Nigeria/ Thailand	0
Rapeseed	China/ Canada/ India/ Germany	3 / 0 / 8 / 0
Soybean	USA/ Brazil/ Argentina/ China	10 / 0 / 0 / 29

terms of irrigation water, the share is slightly higher because of the relatively large share of irrigated sugarcane in the biofuel mix. Total irrigation withdrawals amount to 2,630 km^3 yr^{-1} globally, of which 30.6 km^3 (i.e. 1.7%) are used for biofuel crops (De Fraiture et al. 2008). This estimate includes water for transport biofuels only, not the broader category of biomass for energy.

Water needs for biofuels in future

In some important agricultural areas water is already a constraining factor in food production (Rosegrant et al. 2002; CA 2007). With increasing food demand, there is little excess water and land capacity for large-scale biofuel production. The biggest potential for increasing water use for agriculture can be found in Latin America and Sub-Saharan Africa (Muller et al. 2008). In both areas, less than 5% of the total available renewable water resources are being used, indicating a substantial potential for water use compared to the more than 50% of available water being used in the Near East and South Asia. The potential for irrigation expansion for South Asia, the Middle East and North Africa is reaching its limits (FAO 2006).

Globally, there are sufficient land and water resources (CA 2007), but for some water-scarce countries the situation is more serious. The real problems are in India and China where 35% of the world population lives and where 30-40% of global energy needs are projected to be, by 2030. Both countries have already exploited most of their available natural water resources for agriculture and there is little land and water left to expand areas for crop production (de Fraiture et al. 2008; Muller et al. 2008).

Illustrative calculations of future water use for biofuels (or more broadly bio-energy) provide numbers that differ by an order of magnitude (Table 8.4) but, clearly, they show that the water demand for bio-energy can become large if biomass is promoted to become one of the major primary energy sources.

Figure 8.1 indicates how water use for biofuel feedstock cultivation could develop in different countries/regions. The left end of

Table 8.4 Projections of crop water use and irrigation withdrawals for bio-energy. Lundqvist et al. (2007) estimate crop water requirements and irrigation needs if 30% of the total energy needs are derived from biomass. Pearce Aldhous (2007) assumes that 50% of the energy needs in the transport sector are met by bio-energy by 2050. The estimate by De Fraiture et al. (2008) only includes the liquid biofuel needed to meet 20% of gasoline

Use	**Year**	**Source**	**ET km³**		**Irrigation km³**	
			Low	**High**	**Low**	**High**
Food production	2000	Fraiture et al. 2007	6,800	7,100	2,630	2,850
Food production	2050	Fraiture et al. 2007	8,200	11,300	2,975	4,120
Bio-energy 30% of total energy	2050	Lunqvist et al. 2007	3,917	11,751	1,175	3,525
Bio-energy 50% of transport energy needs	2050	Pearce Aldhous 2007	4,000	12,000		
Multiple scenarios	2050	Berndes et al. 2002	1,000	3,000		
Liquid biofuel 20% of transport needs	2030	Fraiture et al. 2008	270		130	

the respective graphs corresponds to the case where domestically produced biofuels provide 10% of the projected transport fuel use in the respective countries/regions in 2030. The right end corresponds to the case where biofuels provide 50% of total transport fuel use. The more the graph extends to the right the larger is the absolute level of ET from the biofuel feedstock cultivation. The more the graph extends upwards the larger is the relative importance of this biofuel feedstock cultivation for total ET in agriculture in a country/region (total ET is obtained by adding the evapotranspiration from the biofuel feedstock cultivation to the evapotranspiration from food and feed crop cultivation in the base food scenario in the Comprehensive Assessment (CA 2007).

As can be seen, there are large differences in regards to how an expanding biofuel production would add to the total ET in agriculture. There are two major reasons for this. First, the projected transport fuel use in 2030 varies greatly in the different countries/regions. For instance, USA & Canada are together projected to use roughly 50 percent more transport fuels than all the other countries taken together and more than four times as much as China. Second, the analysis assumes that no trade will take place between the countries/regions.

Using the same indicators as in Figure 8.1 above, Figure 8.2 illustrates the water consequences in the case where substantial international biofuels trade takes place. The graph illustrates how large the ET from biofuel feedstock cultivation would be in the different countries/regions producing 25% of the global biofuel demand in 2030 (assumed to range from 10-50% of the total global transport fuel demand in 2030). The difference in how far the lines reach towards the

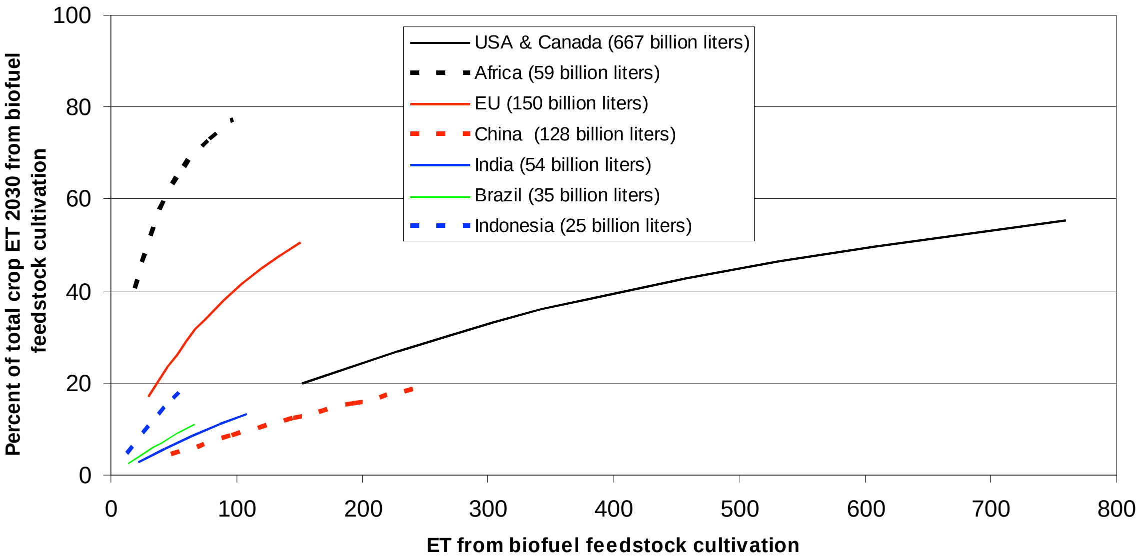

Figure 8.1 ET from biofuel feedstock cultivation in the selected countries/ regions, to support a domestic biofuels production corresponding to 10 percent (lower end) to 50 percent (higher end) of projected transport fuel use in 2030 (Berndes 2008). Based on country/ region-specific water intensity of biofuel routes as in Fraiture et al. (2008). The crop ET in 2030 is estimated from the WATERSIM model (Fraiture et al 2007). The projected transport fuel use in 2030 (IEA 2005) is presented in the legend to the right of each country/ region. Africa is mainly South Africa.

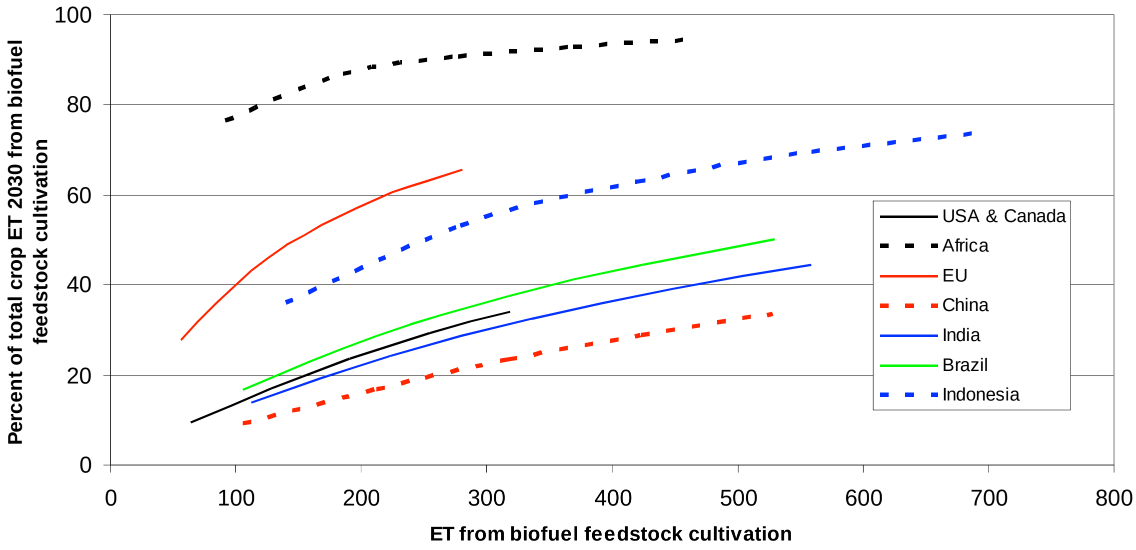

Figure 8.2 ET from biofuel feedstock cultivation in the selected countries/ regions, to support a domestic biofuels production corresponding to 25 percent of the global biofuels use, as the biofuels share increases from 10 percent (lower end) to 50 percent (higher end) of projected transport fuel use in 2030 (Berndes 2008). The country/ region-specific average energy crop ET is kept constant for the total range of biofuel production level, making ET from biofuel feedstock cultivation growing proportionally with the biofuels production volume. See Figure 1 caption for additional information on calculation procedure and data sources.

box 8.1

Uncertainties in Predicting Future Water Demand for Biofuels

It is of course difficult to narrow down the future water demand for bio-energy since it depends on several parameters that are uncertain. For instance:

Percentage of energy demand met by biofuels: This is driven by oil prices and the cost of other transportation energy alternatives (e.g. electric vehicles). It is also determined by policies and economics. Many OECD countries have set mandatory targets for replacement of fossil fuels for reasons of energy security and climate change mitigation. However, high food prices and food insecurity, may drive the focus away from food crops for use as fuel (e.g. China banned maize for biofuel in 2007).

Choice of feedstock depending on technology development and political direction. Will cellulosic biofuels become economically viable in the short term? What is the potential role of non-food, more water-efficient crops such as jatropha and pongamia? What is the potential of crop residues and waste?

The location where energy crops will be grown. From an environmental perspective, land and water-abundant areas would be preferred, though this may run counter to the political objective of national energy security. On the other hand, with lowered trade barriers bio-energy is commonly regarded a step towards improved energy security since the international bioenergy market is expected to see a wide range of net suppliers.

The projected scope of increases in water productivity of main feedstock crops. Particularly, little is known of the water productivity of grasses and wood and its scope for improvements.

Effect of climatic change on crop water use and productivity, particularly for lignocellulosic crops.

right is indicative of the water intensity of the respective biofuel routes in the different regions.

Figures 8.1 and 8.2 indicate the agricultural ET consequences of a biofuel expansion of different scales, but it is not sufficient for making any clear-cut conclusions about the feasibility of large-scale biofuel production in the different countries investigated (see Box 8.1). For this, a comparison with the water resource base is required. For instance, three-quarters of African countries are expected to experience unstable water supplies, where small decreases in rainfall induce much larger reduction in streamflow (de Wit and Stankiewicz 2006). The effects of extensive bio-energy plantations on water use and water balance will be critical to the management of agricultural landscapes and water catchments. Below, possible water impacts as well as pathways to reduce the impacts are described.

Possible water impacts on other uses and ecosystems

In principle, environmental impacts of conventional biofuel crop production are no different from those of other farm crops. Crops require large quantities of water and pursuing biofuel production in water-scarce areas will put pressure on an already stressed resource, in particular if production requires irrigation. In some cases, large-scale biofuel plantations will lead to direct competition with other crops. For example, the Procana project in the Olifants basin in Mozambique foresees the development of 30,000 ha of sugarcane for bioethanol. The project will draw water from a dam that also supports village irrigation schemes (Agencia de Informacao de Mozambique 2007).

Processing plants located near urban areas may compete with cities for scarce and expensive water, as was the case for example in Tampa city in Florida (Economist 2007).

The Millennium Assessment described three types of ecosystem services:

- provisioning services including food, feed, fuel, and timber
- regulating services, such as groundwater recharge, flood control, sediment trapping, water filtering, biodiversity
- cultural and recreational values

Agriculture typically increases provisioning ecosystem services but often (though not always) at the expense of other ecosystem services (MEA 2005). Agricultural water management affects aquatic and terrestrial ecosystems in a number of ways (Gordon et al. 2003). Falkenmark et al. (2007) provide a good overview of possible implications of agriculture on water resources. The most direct and visible effects are related to irrigation but rainfed agriculture also affects ecosystems through land use changes and changes in evapotranspiration. Some of the changes in ecosystems are abrupt, nonlinear, irreversible, and often unexpected (Scheffer et al. 2001).

Effects on aquatic ecosystems

Streamflow reduction and regulation. Water withdrawals from rivers, lakes and groundwater for irrigation lead to reduced streamflow and, in extreme cases, dried-up rivers, at least for prolonged periods during the dry season (e.g. the Yellow river) affecting flora and fauna in the river (Finlayson and D'Cruz, 2005). Some lakes (of which the Aral Sea and Lake Chad are the most infamous examples) are shrinking because of over extraction upstream (Lemoalle 2003; Falkenmark et al. 2007). Reduced river flows due to agricultural diversions upstream may also affect coastal ecosystems because of reduced flushing, as occurs in the San Francisco Bay. Dams and other infrastructure to withdraw water for agricultural purposes fragment river systems and result in an altered streamflow patterns (Vörösmarty et al. 2005). Changes in hydrology affect sedimentation and flooding patterns, fisheries and biodiversity.

Wetland degradation. Wetlands provide essential regulating ecosystem services for water resources (such as retention of flood and sediments, groundwater recharge, baseflow regulation, natural filter, biodiversity). Water regulation and drainage (for agricultural purposes) may be two of the leading causes for loss in wetland areas (Finlayson and D'Cruz 2005). In Southeast Asia, tropical peat swamps have been degraded because of logging for timber and conversion of forests to oil-palm plantations (Wösten et al. 2006). The increased demand for land and water for biofuels may accelerate the drainage of some wetlands. Examples include a proposal from Malaysian and South African investors to convert 300,000–400,000 ha in the wetlands of southern Benin for the production of palm oil, among others, for biodiesel (ABN 2007). Another controversial investment proposal seeks the conversion of wetlands in the Tana delta in northern Kenya into sugarcane for bioethanol (Economist 2007).

Water quality. Direct impacts arise from pollution of runoff from large-scale intensive agriculture (i.e. from fertilizer, pesticide and herbicide application). Fertilizers used to increase agricultural yields (mainly N and P) may end up in waterways and groundwater. Nutrient pollution may have significant impacts on the quality of groundwater and river water and may result in eutrophication of wetlands. For example, excess nitrogen in the Mississippi river has resulted in an anoxic 'dead zone' in the Gulf of Mexico. Diaz and Rosenberg (2008) provide an overview of the severity of this problem worldwide. Other water-quality problems relate to the effluent produced in the production of biofuels. For example, for each liter of ethanol produced in Brazil, about 10-13 liters of a liquid effluent rich in organic matter, called vinasse, are also produced. This effluent contains potassium and phosphorous and can be recycled to the fields substituting commercial fertilizers, but improper management caused many problems of water and soil pollution (Martinelli and Filoso 2008). Chapter 9 (Simpson et al. 2009) gives an in-depth description of water-quality problems related to biofuel crop cultivation.

Effects on terrestrial ecosystems

Changes in water tables. Over pumping of groundwater resources leading to groundwater decline and threatening the sustainability of the resources occurs in India, China, Mexico, western USA and Pakistan, among others (Shah et al. 2007). On the other hand, Australia, among others, has major problems with soil salinization due to rising groundwater levels. Because native vegetation was cleared for pastures and agriculture, consumptive water by natural vegetation has decreased and the water table risen. Salts have moved into the surface soils so that large tracts of land have become less suitable or even unusable for agriculture (Anderies 2005). In the Indus basin, in Pakistan where groundwater is fresh, over pumping leads to groundwater decline, but where groundwater is saline and unusable for agriculture, seepage from irrigation leads to a rise in the ground-water table, salinization, and stagnating water, thus rendering land unusable for agriculture.

Changes in runoff due to land use changes. The effect of conversion of forests into croplands is very site-specific depending on slope, soil, rainfall intensity and land cover (Calder 1999). The impact of energy crops on changes in hydrology has not been studied yet (Uhlenbrook 2007). For example, little is known of the potential hydrological impacts of large-scale conversion of barren land into jatropha plantations in India, which will increase crop transpiration, infiltration, and shading, but will decrease soil evaporation.

Moisture recycling. Large changes in land use and land cover can alter evapotranspiration rates (e.g., from large-scale deforestation) and therefore these changes can alter local climate (Savenije 1995, Falkenmark et al. 2007).

Possible pathways to reduce adverse environmental effects

Use of less water intensive feedstocks, increased water productivity and better water management aimed at supplying a range of ecosystem services can reduce some of the adverse effects of biofuel systems on water resources. We explore each of these pathways in more detail below.

Less-water-demanding crops. Sugarcane and maize, commonly used as feedstock, are highly water-intensive crops. In the main sugarcane areas in Brazil, where rainfall is abundant this is not an issue, but in areas with insufficient or unreliable rainfall they need large quantities of irrigation water. Scientists are experimenting with less-water-demanding crops, such as cassava in China (instead of maize) and jatropha and pongamia in India (instead of sugarcane). Jatropha and pongamia are promoted as water-efficient crops that can be grown on dry and semiarid conditions. India has launched programs to introduce jatropha which is to be planted on 13.4 Mha, mainly on land categorized as 'wastelands' (Rajagopal 2008). In such situations, by acting as biological barriers to soil erosion and reducing the removal of soil nutrients, biofuel crops can make a positive contribution to environmental rehabilitation. But under water-stressed conditions on poor soils the oil yield is low (Jongschaap et al. 2007). Jatropha gives higher yields under irrigation. Therefore, the State Government of Andhra Pradesh is offering a 90% subsidy for drip sets for farmers cultivating jatropha, defeating the argument of low water requirements (Rajagopal 2008). Jatropha is a tree crop that needs a few years before bearing fruits. The seeds of the dominating varieties are not edible and the leaves are not suitable for mulch or fodder (Makkar et al 1997). Some suggest the Indian government would do better to look at a broader range of possible crops that produce byproducts such as residues used as mulch, compost fertilizer and animal feed. Short-duration, multi-purpose crops such as sweet sorghum may prove more suitable than long-term shrubs and tree crops as jatropha (Rajagopal 2008). Lignocellulosic feedstocks, such as grasses and woody crops, are mainly grown under rainfed conditions and can support biofuels production with relatively low water requirements. For processing, water requirements are in the same order of magnitude as for maize- and sugarcane-based ethanol. Currently, they do not compete with food crops for land and water. However, the question remains, if cellulosic biofuels become commercially interesting and perhaps more profitable than food crops, will they encroach on prime agricultural lands? Further, while irrigated grasses are an exception now, with higher-value uses it may become more common.

Increasing water productivity. There is considerable scope for improving water productivity, reducing the amount of water needed for crop production, and leaving more water for other uses, including the environment (Molden et al. 2007a). A recently completed assessment concluded that more than 50% of future water demand for food could be offset by water-productivity improvements. Water management practices include water harvesting, supplementary irrigation, precision irrigation, and soil-water-conservation practices. Factors outside water include improvements in soil fertility, control of pests and diseases, subsidies and better markets. Nevertheless, there are reasons to be cautious about the scope of water-productivity improvement. Crop water productivity is already quite high in highly productive regions, and gains in yields (per unit of land) do not automatically translate into water-productivity gains, or vice versa. Reuse and recycling of water may already be high and perceived losses and inefficiencies lower than generally assumed (Seckler et al. 1998). Further, there is a potential trade-off between water quantity and water quality: agrochemicals needed to improve productivity may adversely affect water quality (Nangia et al. 2008). While breeding of new crop varieties has played an important part in improving the harvest index, and hence water productivity, such large gains are not easily foreseen in the future. Lastly, enabling conditions for farmers and water managers to enhance water productivity are not in place (Molden et al. 2007a).

Managing water for multifunctionality. Many of the water problems arise from large-scale monocultures exclusively managed for one ecosystem service: agricultural or biomass production. A range of ecosystem services (provisioning, regulating, and cultural) can be provided in multifunctional agricultural systems (Falkenmark et al. 2007). Ecosystem-based approaches to water management need not constrain agricultural development. Increased yields can go hand in hand with reduced environmental impacts through increased water efficiency, improved water quality and increased carbon sequestration (Pretty et al. 2006). Biomass for energy can be cultivated in multifunctional plantings that offer extra environmental services. For example coppice, shrubs and grass may act as vegetation filters for treatment of nutrient-bearing water (wastewater from households, runoff from farmlands, or leachate from landfills) (Berndes and Börjesson 2007). Soil-covering plants and vegetation strips can also be located to limit water erosion, reduce direct surface runoff, trap sediment, enhance infiltration, and reduce the risks of shallow landslides (Berndes and Börjesson 2007). This may have positive effects for downstream water resources. Terraced fields in monsoonal climates can reduce soil erosion, enhance infiltration, recharge groundwater, act as a flood-retention basin, and provide a biotope for flora and fauna.

Concluding remarks

Large-scale biofuel production poses both opportunities and challenges to the water sector. Much depends on the choice of feedstock, location of production, current productivity, prevailing agricultural practices and the way water is managed. In some areas there is potential to further develop water resources, though in others, limits of sustainability are already breached. Impacts on downstream uses can be positive as well as negative. The current trends in large-scale agricultural water use mostly point to further aggravation of existing water problems in terms of quantity and quality. However, this need not be the case. Appropriate measures in water management can greatly reduce the adverse environmental impacts and help restore degraded ecosystems. The impacts of biofuel production on water resources will depend on how successful we will be in bringing about the desired changes in agricultural management practices. Regulatory frameworks to ensure sustainable water use in biofuel production are useful, but particularly in countries where institutions to enforce these regulations are weak and multi-nationals can circumvent them, additional incentives will be needed. For example, markets for commodities raised under best managements practices may provide a premium price that rewards voluntary adoption of improved management practices for which compliance is validated by a third party. If links between water use and carbon emissions/sinks can be articulated, funds from carbon markets might become available to improve water management. Multiple approaches to finding creative solutions are needed to ensure sustainable production of biofuels.

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