THE IMPLICATIONS OF LARGE-SCALE ENERGY CROP PRODUCTION FOR GLOBAL WATER USE AND SUPPLY

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ABSTRACT

There are major expectations that bioenergy will supply large amounts of CO_2 neutral energy for the future. In this paper the implications of a large-scale substitution of biomass for fossil fuels are analyzed from a water perspective. The aim is: (i) to estimate how much water that is required to grow biomass and convert it to biofuels or electricity, and (ii) to investigate whether global and regional water resources are sufficient to allow for a large-scale substitution of biomass for fossil fuels in the energy sector. It is found that a large-scale expansion of energy crop production would lead to a large increase in evapotranspiration appropriation for human uses, potentially as large as the present evapotranspiration from global cropland. In some countries this could lead to further enhancement of an already stressed water situation. But there are also countries where such impacts are less likely to occur. One major conclusion for future research is that assessments of bioenergy potentials need to consider restrictions from competing demand for water resources.

1 INTRODUCTION

Global warming —due to the enhanced greenhouse effect— and the associated climate changes is maybe the most pressing and challenging environmental problem. One fundamental concern is the effects of global warming on the hydrological cycle and the impact on the future global and regional water situation. The question of how society directly influences the state of future water systems has received less attention than the question of impacts of climate change on water supply, despite the fact that rising water demands are expected to greatly outweigh climate change in defining the state of global water systems during the coming decades [1]. Especially, the question of how specific strategies for climate change adaptation and mitigation influence future water demands seems partly unexplored.

There are major expectations that biomass will supply large amounts of CO_2 neutral energy for the future. Modernized bioenergy systems are suggested to be important contributors to future sustainable energy systems and to sustainable development [2-4], and several authoritative organizations (e.g., International Energy Agency, World Energy Council, Shell, Greenpeace, UNDP and IPCC) emphasize bioenergy as an attractive option for climate change mitigation in the energy sector. Many scenarios of globally sustainable energy development suggest a huge growth in the use of biomass for energy, with dedicated bioenergy plantations being the major biomass supply source (see [5] for a review of 17 assessments of the global bioenergy potential).

In this paper[1] the implications of a large-scale substitution of biomass for fossil fuels are analyzed from a water perspective. The aim is: (i) to estimate how much water that is required to grow biomass and convert it to biofuels or electricity, and (ii) to investigate whether global and regional water resources are sufficient to allow for a large-scale substitution of biomass for

[1] This paper is based on [6].

fossil fuels in the energy sector. The paper is structured as follows: The water use in energy crop production, and in biomass-based electricity generation and fuels production, is assessed in Section 2. In Section 3, an indication is made of water losses to energy crop evapotranspiration (ET) [2] given that energy crops provide the biomass used for energy in six different scenarios describing possible global energy use and supply up to 2100. The estimated energy crop ET is compared with estimated present evapotranspiration from global cropland. The findings in Section 3 are then used in Section 4, where a scenario of future global water use and availability is constructed, which includes biomass supply for energy corresponding to the most bioenergy-intensive scenario from Section 3. Water-related restrictions on energy crop production of such proportions are analyzed on the national level based on two frequently used water indicators. The implications of the findings are discussed in the concluding section.

2 THE WATER REQUIREMENTS IN ENERGY CROP PRODUCTION AND IN BIOMASS-BASED ELECTRICITY AND FUEL PRODUCTION

The water losses to ET in energy crop production is given for different bioenergy systems in Table 1. The wide ranges in Table 1 can be explained by: (i) varying water use efficiency (WUE)[3] among energy crops, related to crop type, soil and climate, and agronomic practice (including WUE modification options such as changing sowing date and plant density, supplemental irrigation and microclimate manipulation); (ii) variations in the share of the aboveground biomass that is usable as feedstock in electricity/fuels production; and (iii) different conversion efficiencies of technology options available for electricity/fuels production. These aspects are discussed in somewhat more detail in [6, 7]. The lower bound data for energy crop evapotranspiration in Table 1 combine the highest WUE data with options having a conversion efficiency in the upper range of what is found in literature, and where harvest residues and process by-products are used for energy purposes. The higher bound data in Table 1 combine the lowest WUE data with options with lower conversion efficiency that do not use harvest residues or process by-products for energy.

Table 2 presents data for the water requirements in biomass-based electricity/fuels production. Due to the uncertainties involved in assessing prospective technologies, the numbers in Table 2 should be regarded as indicative only. The water that is required to produce the fuels and electricity used at the processing plant is not included. Only the primary biofuel/electricity is accounted for as an energy output. Compared to the evapotranspiration losses in energy crop production, electricity generation consumes little water. This conclusion also applies to the conversion of biomass to fluid fuels. However, the effluent production may be substantial in ethanol production, and also in BIG/GT electricity, hydrogen and methanol production if wet scrubbing of syngas is employed. The relative importance of biomass production versus processing for total water withdrawals depends on how much of the crop water requirements that are met by means of irrigation. The implications of energy crops irrigation will be further discussed in later sections. In the next section, consumptive water use in large-scale bioenergy production is compared with the consumptive water use in present food crop production. The

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[2] Water is lost to the atmosphere in the process of transpiration. Water vapor diffuses from inside the leafs to the atmosphere through the stomata, as carbon dioxide diffuses in the opposite direction. Water is also lost to the atmosphere through evaporation from the soil and from the plant leaves. These losses are collectively designated evapotranspiration losses

[3] The concept water use efficiency (WUE) is a measure of the yield (photosynthetic, biological, or economic) per unit of water (transpiration, evapotranspiration, or applied water). It can be defined on various levels (leaf, plant, field, ecosystem) and for various purposes (agronomic, engineering, basin-level planning). In this paper, WUE is defined as the amount of dry aboveground biomass produced per unit of evapotranspired water.

focus is on energy crops production since this was identified as the major source of consumptive water use in bioenergy production.

Table 1. Energy crop ET per unit bioenergy feedstock and gross bioenergy output. Based on [6, 7].

Biofuel/Feedstock		Water use efficiency[a]	Energy crop ET[b]	
		(kg DM ha^{-1} mm^{-1} ET)	(Mg GJ^{-1} feedstock)	(Mg GJ^{-1} gross el./fuel output)
Biodiesel	rapeseed	9-12	46-81	100-175
Ethanol	sugarcane	17-33	23-124	37-155
	sugar beet	9-24	57-151	71-188
	corn	7-21	37-190	73-346
	wheat	6-36	21-199	40-351
Lignocellulosic crops		10-95		
Ethanol			7-68	11-171
Methanol			7-68	10-137
Hydrogen			7-68	10-124
Electricity			7-68	13-195

[a] The water use efficiency is given as kg aboveground DM mm^{-1} evapotranspiration (ET). The depth of water supply is often given in mm, where one mm corresponds to 10 Mg water ha^{-1}. 50 kg DM mm^{-1} is equivalent to a water loss as ET of 200 g per g DM produced. See [7] for original references. DM=dry matter.

[b] Lower range numbers refer to systems where: (i) harvest residues from non-lignocellulosic crops (50 percent of total) are used for power production (at 45 percent efficiency); or (ii) higher efficiencies in processing lignocellulosic crops are achieved. When ethanol is produced from sugarcane or lignocellulosic feedstocks, process by-products (bagasse and lignin, respectively) are used for internal heat and electricity. Here, lower range numbers refer to systems designs allowing for export of electricity in excess of internal requirements.

Table 2. Indicative data on water requirements in biomass-based fuel production and electricity generation. Based on [6].

Bioenergy option	Mg GJ^{-1} gross el./fuel output[a]
Electricity generation	
Total thermoelectric generation in USA 1995	0.5[b]
Biomass-based steam plants constructed in USA in the mid-1980's	0.7
Improved biomass-based steam plant	0.5
Gasification-based biomass electricity	0.1
Fluid biofuels	
Hydrogen, gasification, shift reaction and reforming	0.1-0.3
Methanol, gasification, shift reaction and reforming	0.05-0.1
Quench feed water for wet scrubbing of syngas exiting biomass gasifier	0.03-0.9 (methanol)
	0.2-4.6 (hydrogen)
Ethanol based on pine, process water	0.1-6.5
Ethanol production, stillage yield	0.5 (beet molasses)
	0.7 (cane juice)
	0.6 (cane molasses)
	0.5 (cellulosics)

3 EVAPOTRANSPIRATION FROM LARGE-SCALE ENERGY CROP PRODUCTION

Figure 1 presents the evapotranspiration from the energy crop production required to supply the biomass for energy in six energy scenarios produced by the International Institute for Applied Systems Analysis (IIASA) and the World Energy Council (WEC) [8]. The scenarios represent very different evolutions of energy demand and supply patterns over the 21st century, and thus span over a wide range of possible futures. The global biomass supply for the production of commercial energy carriers (such as electricity, hydrogen and alcohols) grows in all scenarios, but at quite different rates: it ranges from 47 to 123 EJ yr^{-1} in 2050 and from 157 to 304 EJ yr^{-1} in 2100.

It is assumed that lignocellulosic energy crops provide the total biomass supply for energy since such crops are generally expected to be the major source of biomass for energy in the future[4]. The global average energy crop evapotranspiration is set to 25 Mg per GJ feedstock, which implies a WUE of about 2.5 g DM per kg water if 80 percent of aboveground DM is usable for energy purposes. This WUE is in the lower half of the range for lignocellulosic crops in Table 1 (1-9.5 g DM per kg water). But, the extraordinary high upper bound given for lignocellulosic crops (cultivation of Miscanthus giganteus in southeast England [9]) illustrates what can be reached under favorable conditions rather than indicates average WUE:s that could be achieved over large areas around the world. Kinzig *et al.* [10] designated, for example, a WUE of 3 g DM per kg water as “optimistic” in their modeling of large-scale biomass production for energy in Northeast Brazil. The estimated present global cropland evapotranspiration (including evapotranspiration from weeds and vegetation in open drainage ditches, green enclosures, and wind breaks) is included in Figure 1 as a comparison [11]

[4]The total energy crop evapotranspiration will of course be lower if residues and process by-products from the food and forest sector provide a share of the biomass supply for energy. If, for example, 25 percent of biomass supply for energy were provided from residues, then the curves in Figure 2 would be 25 percent lower. The land use requirements of the two most biomass-intensive scenarios A2 and A3 were estimated by in a post-scenario feasibility test [8]. Lower bound estimates assumed that 80 percent (2050) and 67 percent (2100) of biomass was produced from plantations. Higher bounds assumed 100 percent plantations.

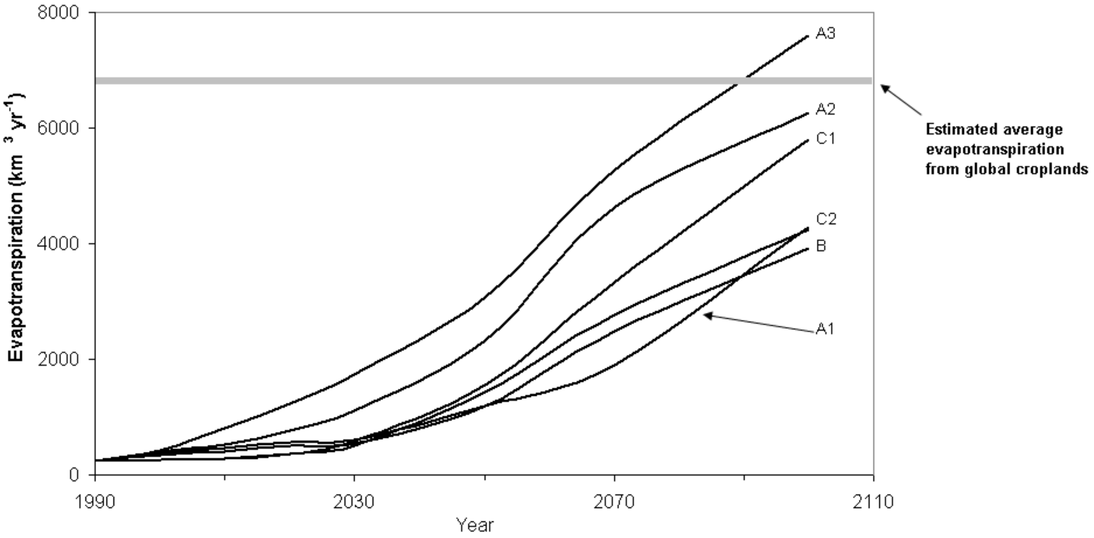

Figure 2. Evapotranspiration from energy crops production in the IIASA/WEC scenarios, and estimated evapotranspiration from global cropland. Based on [6].

Figure 1 clearly shows that an expansion of energy crop production to scales indicated by the IIASA/WEC study might introduce a new appropriation of evapotranspiration that can be as large as the present global crop production. As was shown earlier, the WUE vary significantly. It is easy to imagine water use efficiency levels that are a factor of two higher or lower. The graphs in Figure 1 would then change accordingly. However, considering the unpredictability of factors influencing the evapotranspiration per unit biomass (e.g., climate change, crop choice, biotechnology development, land use practices and relative cost of land, water and other inputs) a more refined approach, such as using different WUE for different regions, is hard to motivate. Besides, the purpose has not been to provide exact estimates of global evapotranspiration from large-scale energy crop production, but to provide indications of the increase of evapotranspiration requirements that can be expected if large areas were dedicated to energy crops production.

The incidence of energy crops irrigation is difficult to project, but it can lead to substantial additional withdrawals if employed extensively. Assume, for example, that 15 percent of the energy crop evapotranspiration in the six IIASA/WEC scenarios was provided by means of irrigation. If the average efficiency in irrigation water supply is 50 percent, then up to 370 km^3 of additional water would have to be withdrawn in 2025. In year 2100, up to 2281 km^3 of additional water would have to be withdrawn. This can be compared with the present withdrawal for irrigation estimated at roughly 2000-2900 km^3 yr^{-1} [12-15]. Clearly, such additional withdrawals for energy crop irrigation would lead to substantial increases in total withdrawals.

4 A SCENARIO OF FUTURE WATER USE AND AVAILABILITY

4.1 Scenario construction and analysis

Below, a scenario of future water use and availability is constructed, which includes an expanding bioenergy sector that use biomass plantations as the main feedstock source. Data on present and future water withdrawals (excluding bioenergy requirements) and availability are taken from the “best guess” M scenario in [16]. The data are modified to include additional water demands from an expanding bioenergy sector. The IIASA/WEC A3 scenario is used here. It is the most biomass-intensive scenario in the IIASA/WEC study, reaching a biomass supply of 304 EJ yr^{-1} in the year 2100. The IIASA/WEC scenarios are developed on a regional level. The regional scenarios have been scaled down to a country by country basis, e.g., Argentina is assumed to produce as much bioenergy as Latin America as a whole on a per capita basis.

An expanding bioenergy sector potentially competes for water in two ways: (i) by withdrawing water for irrigation of energy crops, and for cooling and other el./fuel plant uses, or (ii) by increasing the evapotranspiration on the land where energy crops are cultivated. Establishment of bioenergy plantations can lead to increased evapotranspiration, especially if tree crops replace shallow-rooted grasses, herbs, or food crops [17]. The redirection of rainfall from runoff and groundwater recharge to evapotranspiration may significantly reduce downstream water availability. Thus, the impact of bioenergy feedstock production is modeled in two alternative ways in the scenario:

- As an additional withdrawal, where 15 percent of the water that is lost to energy crop evapotranspiration in each country is assumed to be supplied by means of irrigation (with an average irrigation efficiency of 50 percent), increasing the total withdrawals year 2075 as given in [16]. The rainfed energy crop production is assumed not to reduce water availability in this case.

- As a reduction in the water availability year 2075 due to a redirection of rainfall from runoff to energy crop evapotranspiration. Here, it is assumed that the reduction corresponds to one third of energy crop evapotranspiration. No irrigation of energy crops takes place in this case.

The resulting water requirements and availability are analyzed based on two frequently used indicators.

- The *water barrier concept* [14, 18] classifies countries based on the water availability per capita. Below 500 m^3 cap^{-1} a country faces *absolute water scarcity*, between 500 and 1000 m^3 cap^{-1} *water scarcity*, and between 1000 and 1700 m^3 cap^{-1} *water stress*. Countries having more than 1700 m^3 cap^{-1} are classified as having sufficient water.

- The *use-to-resource ratio* complements the water barrier concept. Here, *use* refers to water withdrawals and *resource* refers to water availability. A ratio of 25 percent is taken to be indicative of *water stress* following [14].

It should be kept in mind that these indicators are only weak indications of water scarcity. Thresholds for water scarcity and stress can vary greatly between countries depending on the structure (and water intensity) of economic activities and on the institutional capacity to adapt to water scarcity. For instance, low levels of water availability may be dealt with by importing food [19-21]. Countries without any water scarcity according to these measures may run into problem if the water in reality is largely unavailable. For example, Postel *et al.* [13] estimate that 95 percent of the Amazon River flow is inaccessible to humans. On a global scale, about one-third of total runoff is estimated realistically available for human use [13].

The scenario construction does not capture suggested water-related beneficial aspects of energy crop production. Energy crops can be grown as vegetation filters for treatment of nutrient rich municipal wastewater and drainage water, thereby mitigating groundwater pollution and eutrophication [22, 23]. The benefits of tree plantations for water erosion control and flood prevention are extensively documented, and afforestation of deforested watersheds leads to reduced sediment load in reservoirs and irrigation channels [17]. Large-scale planting of trees are used for salinity management on land subject to productivity losses due to soil salinity induced by rising water tables. Agroforestry systems can increase productivity in rain-fed agriculture by capturing a larger proportion of the annual rainfall in areas where much of the rainfall occurs outside the normal growing season [24]. In-field soil evaporation and evaporating surface runoff can be redirected to energy crop transpiration, leading to increases in the productive use of evapotranspiration[5]. Thus, one strategy for water scarcity adaptation can be to use biomass production for energy as a tool for increasing the spatial and temporal accessibility of water resources and at the same time improve the quality of freshwater flows.

Figure 2 shows the results for a selection of countries (the results for 42 countries —covering about three-fourth of the total global land area, and having almost 90% of global arable land and land under permanent crops— are presented in [6]). Filled dots represent the situation in 1995. Two arrows originate from each dot and point to the situation in year 2075, according to the two scenario variants. The one moving furthest towards the y-axis represents the zero irrigation case (and therefore a reduction in water availability). The other arrow (reaching furthest upward) represents the irrigation case. Keep in mind that the water uses in other sectors increase as well, and the per-capita water availability changes due to population growth and climatic change.

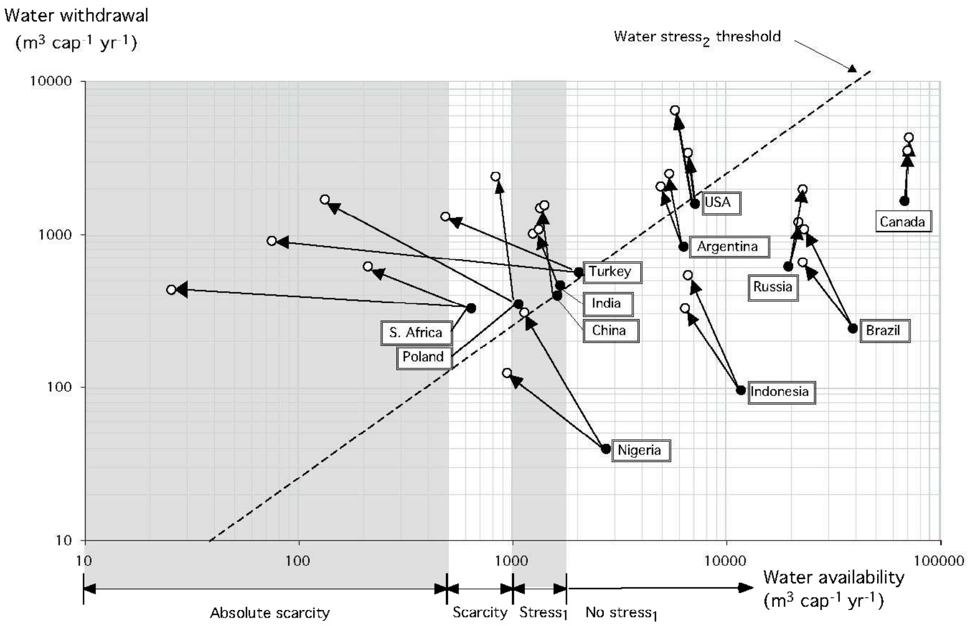

Figure 2. Per-capita water withdrawal and availability for a selection of countries in the scenario. Filled dots represent the situation in 1995. The water barrier indicators are included along the x axis, and the use-to-resource ratio is included as a dashed line representing the combinations of water withdrawal and availability that leads to a ratio of 25 percent. This line is designated Water stress$_2$ threshold.

Some tentative conclusions can be drawn:

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5 Trees in agroforestry systems may improve micro-climate for understorey crops leading to increased water-use efficiency, but they also compete for water and nutrients. The net effect of beneficial and detrimental influence on understorey crops vary [25-27]. The net *income generation* effect of establishing agroforestry systems depend on the relative values of potential carbon sinks, wood harvest and crop harvest.

- Water availability appears not to impose a constraint on the assumed level of bioenergy production in countries such as Canada, Brazil, Russia, Indonesia and in several countries in sub-Saharan Africa.

- Several countries (e.g., South Africa, Poland, Turkey, China, and India) are already facing a scarce water situation, which is projected to become increasingly difficult even if large-scale bioenergy feedstock production would not materialize.

- Other countries, such as USA and Argentina, are projected to join the group of countries that withdraw more than 25 percent of available water. The reason is large per-capita withdrawals rather than scarce availability.

Obviously, countries having sufficient water resources will have to produce more than the region-average amount of biomass for energy in order to ensure the total regional bioenergy output, if scarce water resources prevent a large number of countries in the same region from providing the region-average amount.

4.2 Sensitivity with respect to critical assumptions

There are several assumptions that are crucial for the outcome of the scenario, primarily the water use efficiency, share of evapotranspiration supplied from irrigation, irrigation efficiency, and the extent to which rainfed energy crops production reduces downstream water availability.

Water use efficiency has been put constant across regions and over time in the scenario. Thus, the purpose has not been to provide exact estimates of global evapotranspiration from energy crops production. Rather, the purpose is to provide indications of the changes that can be expected. It is easy to imagine water use efficiency levels that are a factor of two higher or lower, and the estimated global and country specific water use levels would change accordingly.

The extent to which energy crops will actually be irrigated depends on the economics of such systems, local water availability and many other factors. The 0% and 15% assumptions are largely arbitrary, and doubling the 15% assumption would double the water use levels. As have been illustrated, rainfed biomass production could potentially lead to a similar impact on the national water situation, by re-directing water runoff to evapotranspiration. Still, the increased amount of water lost to evapotranspiration is very uncertain, site specific, and depends on the vegetation that was replaced.

As already mentioned, in some areas where high water tables and soil salinity cause productivity losses, increased evapotranspiration is a welcome feature of established plantations. In other areas, reduced downstream availability of water may lead to increased stresses in an already difficult situation. An important topic for future research is the potential for bioenergy production given basin scale competition for water.

The scenario that provided the basis for the scenario construction defines water availability as the sum of modeled river runoff and groundwater recharge. This is a rough approximation of water availability. The projected long-term water availability also depends on the precipitation estimates of the general circulation models used, which are generally less reliable than their temperature estimates [16].

Major rivers flow through areas remote from population centers, and a long distance from potential crop land (for food or energy crops). In addition to geographical restrictions on availability, there are also temporal restrictions. A large part of global runoff is flood water, and capturing this flow generally requires dams for storage. Thus, the long-term practical availability of water resources is uncertain. Future temporal accessibility depends on dam-building rate, and geographically inaccessible runoff can be made accessible by diverting remote river flows. Temporal and geographical resource accessibility is also highly variable among countries, and country borders in themselves introduce difficulties since the appropriate scale for assessing water availability is the watershed scale [16].

5 CONCLUDING DISCUSSION

This analysis has provided a birds-eye view on the implications of an expanding bioenergy sector for the future use and availability of water resources. One conclusion is that a large-scale expansion of energy crop production would lead to a large increase of evapotranspiration appropriation for human uses, potentially as large as the present evapotranspiration from global cropland. In some countries such an expansion would lead to further enhancement of an already stressed water situation. In others presently not stressed countries, a large-scale expansion could induce a more difficult situation. But there are also countries where such impacts are less likely to occur. Even though the incidence of energy crops irrigation is of crucial importance, the influence of rain-fed production can also be significant in water-scarce regions.

One major conclusion for future research is that assessments of bioenergy potentials need to consider restrictions from competing demand for water resources. Tools developed for analysis of the future use and availability of water can provide important insights into basin-scale capacity to provide large amounts of biomass for energy. Basin level planning should include biomass production as a land use option with potential for combining erosion control and flood prevention with income generation from carbon sink generation and biomass sales for energy.

6 ACKNOWLEDGEMENTS

Financial support from the Swedish Energy Agency is gratefully acknowledged.

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