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Future Biomass Energy Supply: The Consumptive Water Use Perspective

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ABSTRACT *There are major expectations that bioenergy will supply large amounts of CO_2 neutral energy for the future. 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. However, there are also countries where such impacts are less likely to occur. Studies that assess bioenergy potentials need to consider restrictions from competing demand for water resources. Studies of the future state of water availability and use need to include the possibility of new high demands for water from a growing bioenergy sector.*

Introduction

Many studies suggest that biomass can become an important primary energy source in the future global energy system, with dedicated biomass plantations being the major biomass supply source (see Berndes *et al.*, 2003 for a review). The impact of plantation establishment on water availability and use depends on site-specific conditions and prior land use/vegetation cover. To the extent that plantation establishment leads to higher site productivity and biomass accumulation then it can be expected that the evapotranspiration (ET) increases. Compared to food crops, shrubs and pasture vegetation, plantations often have high productivity and annual transpiration and rainfall interception, particularly for evergreen species. Expanding plantations on such land will, thus, often lead to increases in ET and reductions in streamflow. Since plantation establishment on abandoned agricultural land and sparsely vegetated degraded land is one major option suggested for a large-scale bioenergy expansion, the water use dimension of expanding bioenergy needs to be carefully investigated.

However, few studies have addressed the issue so far. Berndes (2002) reports that the large-scale expansion of bioenergy plantations would lead to a large increase in ET appropriation for human uses, potentially as large as the present ET from global cropland. In some countries this could lead to further enhancement of an already stressed water

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situation, while water constraints are less likely to occur in other countries. Studies primarily discussing plantation establishment aiming at carbon sequestration are also relevant for the bioenergy case. Based on a global analysis of 504 annual catchment observations, Jackson *et al.* (2005) report that afforestation dramatically decreased streamflow within a few years of planting. Across all plantation ages in the database, afforestation of grasslands, shrublands or croplands decreased streamflow by, on average, 38%. Average losses for 10- to 20-year-old plantations were even greater, reaching 52% of streamflow. From a global analysis of land suitability and water use impacts of afforestation/reforestation (AR) meeting the eligibility criteria for AR projects within the Clean Development Mechanism (CDM), Zomer *et al.* (2006) report that large areas deemed suitable for CDM-AR would exhibit ET increases and/or decreases in runoff, i.e. a decrease in water potentially available off-site for other uses. This was particularly evident in drier areas, the semi-arid tropics, and in conversion from grasslands and subsistence agriculture.

The aim of this paper is first to give a brief introduction to bioenergy and indicate its prospective size in relation to other biomass uses, and second to discuss the implications of a large expansion in the use of biomass for energy from a water perspective. The amount of water that is required to grow biomass and convert it to biofuels or electricity is estimated, and used 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. The paper builds further on work reported in Berndes (2002) and the reader is referred to this publication for more information and a full list of references.

The Role of Biomass among Renewable Energy Sources

Today, technology development has put us in a situation where industry can produce biobased products with a quality that satisfies a high consumer demand. This opens up a wide range of options for the substitution of fossil resources. In addition to traditional products such as paper and textiles, new types of biobased products—including biodegradable plastics, biocomposites, bulk chemicals and biofuels for transport—compete with the established petroleum based alternatives.

Figure 1 provides perspectives on the prospects for biomass to substitute for fossil resources in the future by providing a quantification of the biomass production for food, energy and materials together with fossil resource flows. As can be seen, the quantitative production of fossil resources is much larger than the biomass production in agriculture and forestry, implying that a far-reaching substitution of fossil resources with biomass would require a dramatic increase in the output from agriculture and forestry. Petroleum is, to some extent, used for the production of plastics and bulk chemicals, some 10–15% of the coal is used in steel production and fossil gas (and also to some extent other fossil resources) is used for the production of synthetic fertilizers. However, it is the use of fossil fuels in the energy sector that is the dominating source behind society's exploitation of fossil resources. Therefore, it is the substitution of fossil resources in the energy sector that may entail the largest increase in biomass use and thus human appropriation of evapotranspiration.

Energy supply from biomass has been assigned an important role among renewable energy sources (RES) in several world regions. Biomass is one of the RES already available today for climate change mitigation and is also regarded as one key option for

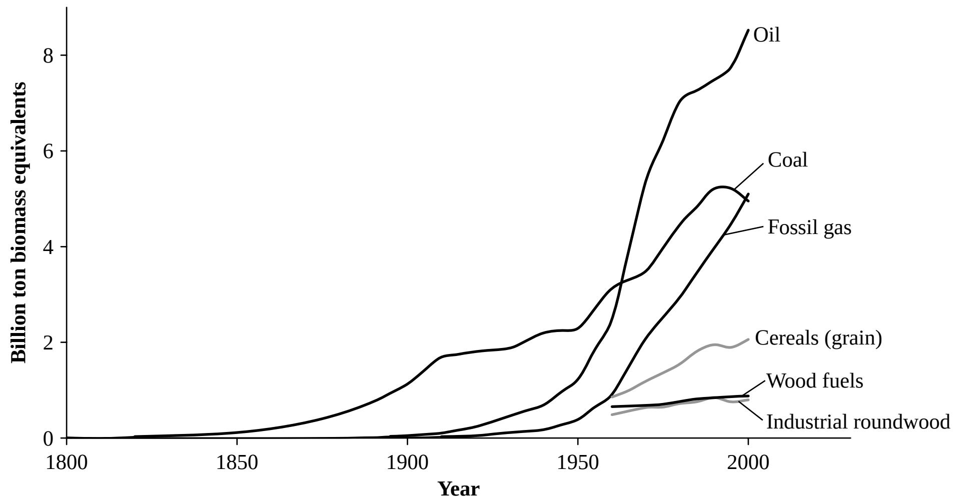

Figure 1. Global annual production of major biomass types in agriculture and forestry and fossil resources. The fossil resources are given on a biomass equivalent basis (be) in order to facilitate a comparison with the different biomass types (conversion based on 1 ton oil equivalent = 42 GJ; 1 ton be = 18 GJ). 'Wood fuels' (FAO data) does not include all biomass uses for energy. For example, the FAO 'Wood fuels' data for year 2000 corresponds to about 15 EJ, while the global biomass use for energy is estimated at about 35–55 EJ/ year. *Source:* Based on Berndes (2006).

reducing dependency on imported fuels in countries relying on imported oil and natural gas. The use of biofuels for the production of heat and electricity has been successfully increased in countries such as Finland and Sweden. As the utilization has increased, the techniques and technologies to collect, transform and transport biomass have improved and costs have decreased. Due to such developments there are optimistic scenarios suggesting that biofuels could also be used to substitute significant parts of the fossil fuels used for transport. Stimulated by directives and regulations, the use of so-called 'first generation' biofuels, such as ethanol and biodiesel based on traditional starch, sugar and oil crops, has currently increased in, for example, the European Union, North and South America and Asia/Pacific. Second generation liquid biofuels, such as Fischer-Tropsch fuels, Dimethyl Ether, lignocellulose based ethanol and biohydrogen, are envisioned to become increasingly competitive to their fossil alternatives as technologies develop and allow production based on more abundant and potentially much cheaper lignocellulosic feedstocks such as straw, forest residues and lignocellulosic energy crops.

As an illustration of the magnitude and implications of bioenergy targets in contemporary energy policy, Figure 2 presents the cereal production in the world together with the potential agricultural biomass supply for energy reported in a joint United States Department of Agriculture (USDA)/United States Department of Energy (DOE) assessment supporting the US 'Billion-ton vision' for the year 2030 (Perlack *et al.*, 2005). According to the assessment, more than 1.3 billion dry US tons of biomass per year could be supplied from forests and agricultural land, with about 73% of this from agriculture. The goal set by the Congress-established Biomass Research and Development Technical Advisory Committee to displace petroleum, corresponding to 30% of the

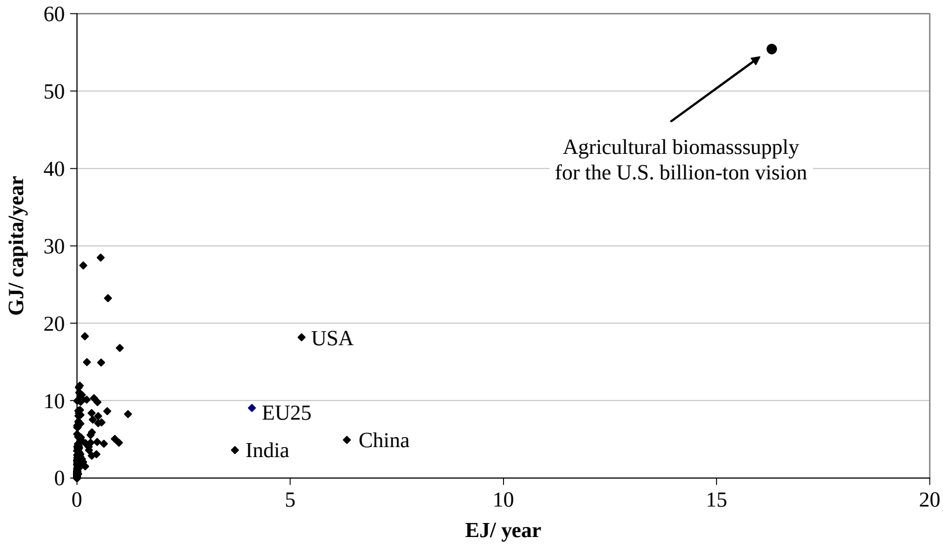

Figure 2. Agricultural biomass supply for the US 'billion-ton vision' compared to present cereal production in the world. The agricultural biomass supply consists of residues (54%) and dedicated energy crops (46%). Recalculation to energy units assuming 18 GJ/ton DM biomass and assuming that the average DM content of harvested cereals is 90%. *Sources:* Based on Perlack *et al.* (2005) and FAO Statistical Databases (available at http://www.fao.org).

present petroleum consumption in the USA, would require about 1 billion dry US ton of biomass (Note: 1 US ton is approximately 0.9 metric ton, which is referred to as 'ton' in this paper).

As can be seen, the agricultural biomass supply for energy envisioned is very large compared to this other major biomass supply in agriculture. What is also evident from Figure 2 is that agricultural residues (54% of total biomass supply from agriculture in the 'billion-ton-vision') can provide a substantial input to bioenergy. Such biomass categories have the advantage that their utilization does not induce new dedicated cultivation. The utilization of residues for energy thus mitigates the demand on water for bioenergy: the water that is consumptively used to produce the primary products in agriculture (and also forestry) is the same water that will also produce the residues. However, the residue utilization can lead to negative effects, such as soil degradation, if it is not restricted to acceptable levels.

The Biomass-related Water Requirements

The water losses to evapotranspiration (ET) in biomass production are given for different bioenergy systems in Table 1. The wide ranges in Table 1 can be explained by: (1) varying water use efficiency (WUE) 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; (2) variations in the share of the above ground biomass that is usable as feedstock in electricity/fuels production; and (3) different conversion efficiencies of technology options available for electricity/fuels production.

Table 1. Energy crop ET per GJ bioenergy feedstock and gross bioenergy output

Biofuel	Feedstock	Energy crop ET[a] (ton water per GJ of feedstock)	Energy crop ET[a] (ton water per GJ of gross electricity or biofuel output)
Traditional food crops			
Biodiesel	Rapeseed	46–81	100–175
Ethanol	Sugarcane	23–124	37–155
	Sugar beet	57–151	71–188
	Corn	37–190	73–346
	Wheat	21–199	40–351
Lignocellulosic crops [b]		7–68	
Ethanol			11–171
Methanol			10–137
Hydrogen			10–124
Electricity			13–195

Notes: [a]Lower range numbers refer to systems where: (1) harvest residues from non-lignocellulosic crops (50% of total) are used for power production (at 45% efficiency); or (2) 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 system designs allowing for export of electricity in excess of internal requirements.
[b]For example, short rotation woody crops such as Salix and Eucalyptus and grasses such as Miscanthus and Switchgrass.
Source: Based on Berndes (2002).

The present ethanol production based on traditional food crops can be used as an illustrative example. When ethanol is produced from sugarcane or sugar beet, only the sugar in the crops is used as feedstock. When ethanol is produced from cereals such as wheat or corn, only the starch-rich grain is used. On a dry matter (DM) basis, approximately 25% of above ground sugarcane growth, and about 40% of sugar beet whole-plant mass, is sugar (Wirsenius, 2000). The ratio of grain to total above ground DM varies significantly among cereals, but it is usually below 0.5 (Wirsenius, 2000). Therefore, less than half of above ground growth (with resulting ET) is usable as feedstock when ethanol is produced from sugar crops or cereals. However, the use of harvest residues and process by-products for process heat or additional fuel and electricity production can lower the evapotranspiration per GJ bioenergy output substantially. Sugarcane-ethanol factories, for example, use the process by-product bagasse for cogeneration of process heat and electricity. If steam-conserving technologies are combined with advanced technologies for electricity generation, an ethanol factory can use bagasse and sugarcane trash to generate all process heat and more electricity than is needed in the factory. System designs that combine ethanol production with off-season electricity generation can export almost 600 kWh electricity and 85 litres ethanol per ton of sugarcane processed (Larson & Kartha, 2000).

The lower bound data for energy crop ET in Table 1 combine the highest WUE data found in a literature survey (see Berndes, 2002) with technology options having conversion efficiencies in the upper range of what is found as reported 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 technology options having lower conversion efficiencies and where no harvest residues or process by-products are used for energy.

Compared to the ET losses in biomass production, the subsequent conversion to fuels or electricity generation consumes little water, typically a factor 100 less (Berndes, 2002). However, the effluent production may be substantial in ethanol production, and also in electricity, hydrogen and methanol production if wet scrubbing of syngas is employed. The relative importance of biomass production versus conversion for total water withdrawals depends on how much of the crop water requirements are met by means of irrigation.

The implications of energy crop irrigation will be discussed further in later sections. In the next section, the consumptive water use in large-scale biomass production is compared with the consumptive water use in present food crop production.

Evapotranspiration from Large-scale Bioenergy Production: Six Scenarios

Figure 3 presents the ET from the energy crop production that is required to supply the biomass used for energy in six energy scenarios produced by the International Institute for Applied Systems Analysis (IIASA) and the World Energy Council (WEC) (Nakicenovic *et al.*, 1998). While population growth is the same in all scenarios, reaching 10 billion in 2050 and nearly 12 billion in 2100, they 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 three 'high growth' A scenarios range from assuming that high availability of oil and gas resources leads to dominance of oil and gas until the end of the 21st century (A1), to assuming that oil and gas scarcity leads to massive return to coal (A2), or that rapid technological development in nuclear and renewable energy technologies leads to fossil fuels being out-competed (A3). The B scenario represents a middle course with more modest economic growth and lower energy demand than in the A scenarios, but higher energy demand than in the two C scenarios, which are optimistic

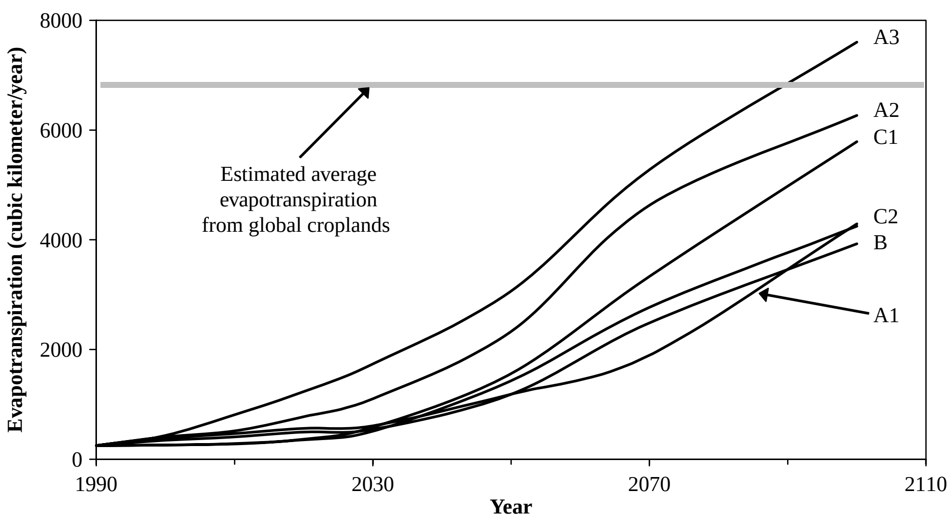

Figure 3. Evapotranspiration from energy crop production in the IIASA-WEC scenarios, and estimated evapotranspiration from global cropland. See text for assumptions. Reprinted from *Global Environmental Change*, vol. 12, Berndes, G., Bioenergy and water—the implications of large-scale bioenergy production for water use and supply, pp. 7–25, © 2002, with permission from Elesvier.

about technology development while emphasizing international cooperation and equity and also environmental protection. C1 assumes a complete phaseout of nuclear power, while C2 assumes nuclear expansion.

Common to all the scenarios is that the global biomass demand for the production of commercial energy carriers (such as electricity, hydrogen and alcohols) grows over time, but at quite different rates: it ranges from 47 to 123 EJ/yr in 2050 and from 157 to 304 EJ/yr in 2100.

The energy crop ET in Figure 3 is calculated based on the assumption 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. The global average energy crop ET is set to 25 tons of water per GJ feedstock, which implies a WUE of about 2.5 g DM per kg of water if 80% of above ground DM is usable for energy purposes. This can be compared with the ET from lignocellulosic crops in Table 1, at 7–68 tons of water per GJ feedstock. The estimated present global cropland ET (including ET from weeds and vegetation in open drainage ditches, green enclosures and wind breaks) is included in Figure 3 for comparison (Rockström *et al.*, 1999). The energy crop ET 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, residues contributed 25% of the biomass supply for energy, then the curves in Figure 3 would be 25% lower.

Figure 3 clearly shows that an expansion of energy crop production to scales indicated by the IIASA/WEC study might introduce a new appropriation of ET that can be as large as the present global crop production. As shown earlier, the WUE varies significantly. It is easy to imagine WUE levels that are a factor of two higher or lower. The graph in Figure 3 would then change accordingly. However, considering the unpredictability of factors influencing the ET 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. In addition, the purpose has not been to provide exact estimates of global ET from large-scale energy crop production, but to provide indications of the increase of ET requirements that can be expected if large areas were dedicated to energy crop production.

The incidence of energy crop irrigation is difficult to project, but it can lead to substantial additional withdrawals if employed extensively. Assume, for example, that 15% of the energy crop ET in the six IIASA/WEC scenarios was provided by means of irrigation. If the average efficiency in irrigation water supply were 50%, then up to 370 cubic kilometres (km^3) of additional water would have to be withdrawn in 2025. In the year 2100, up to 2281 km^3 of additional water would have to be withdrawn. This can be compared with contemporary estimates of global withdrawals for irrigation, approximately ranging from 2000 (Raskin *et al.*, 1995) to 2,900 km^3/yr (Postel *et al.*, 1996). Clearly, withdrawals for energy crop irrigation could lead to substantial increases in total withdrawals for irrigation.

Implications for Future Water Use and Competition

Below, a scenario of future water use and availability is constructed, which includes an expanding bioenergy sector that uses 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 Alcamo *et al.* (1997). The data are modified to include additional water demands from an expanding bioenergy sector. The most biomass-intensive IIASA-WEC A3 scenario is used here, reaching a biomass supply of 304 EJ/yr in the year 2100. The IIASA-WEC scenarios are developed on a regional level. These regional scenarios have been scaled down on a country-by-country basis, e.g. Argentina is assumed to produce as much bioenergy, on a per capita basis, as Latin America, on the whole.

An expanding bioenergy sector potentially competes for water in two ways: first, by withdrawing water for irrigation of energy crops, for cooling and other electricity/fuel plant uses, or second, by increasing the ET on the land where energy crops are cultivated. Establishment of bioenergy plantations can lead to increased ET, especially if tree crops replace shallow-rooted grasses, herbs or food crops. The redirection of rainfall from runoff and groundwater recharge to ET may significantly reduce downstream water availability. Therefore, the impact of bioenergy feedstock production is modelled in two alternative ways:

- as an additional withdrawal, where 15% of the water that is lost to energy crop ET in each country is assumed to be supplied by means of irrigation (with an average irrigation efficiency of 50%), increasing the total withdrawals in the year 2075 as given in Alcamo *et al.* (1997). The rain-fed energy crop production is assumed not to reduce water availability in this case; and
- as a reduction in the availability of water in the year 2075 due to a redirection of rainfall from runoff to energy crop ET. Here, it is assumed that the reduction corresponds to one third of energy crop ET. No irrigation of energy crops takes place in this case.

The resulting water requirements and availability are analyzed based on two frequently used indicators: (1) the water barrier concept where countries are classified based on the per capita water availability (Falkenmark, 1989); and (2) the use-to-resource ratio, which complements the water barrier concept. Here, use refers to water withdrawals and resource refers to water availability.

Figure 4 shows the results for selected countries. The results for 42 countries, covering approximately three-quarters of the total global land area, and having almost 90% of global arable land and land under permanent crops, are presented in Berndes (2002). The filled dots in Figure 4 represent the situation in 1995. Arrows originate from each dot and point to the situation in the year 2075, according to the two scenario variants (hollow dots). The hollow dots that are furthest towards the y-axis represent the zero irrigation case (and therefore a reduction in water availability). The other hollow dot (reaching the furthest upward) represents the irrigation case. It should be remembered that the water uses in other sectors increase as well, and the per capita water availability changes due to population growth and climatic change.

Some tentative conclusions can be drawn: (1) 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; (2) Several countries (e.g. South Africa, Poland, Turkey, China and India) are already facing a situation of water scarcity, which is projected to become increasingly difficult even if large-scale bioenergy production does not materialize; and (3) other countries, such as the USA and Argentina, are projected to join the group of countries that withdraw more than 25% of available water.

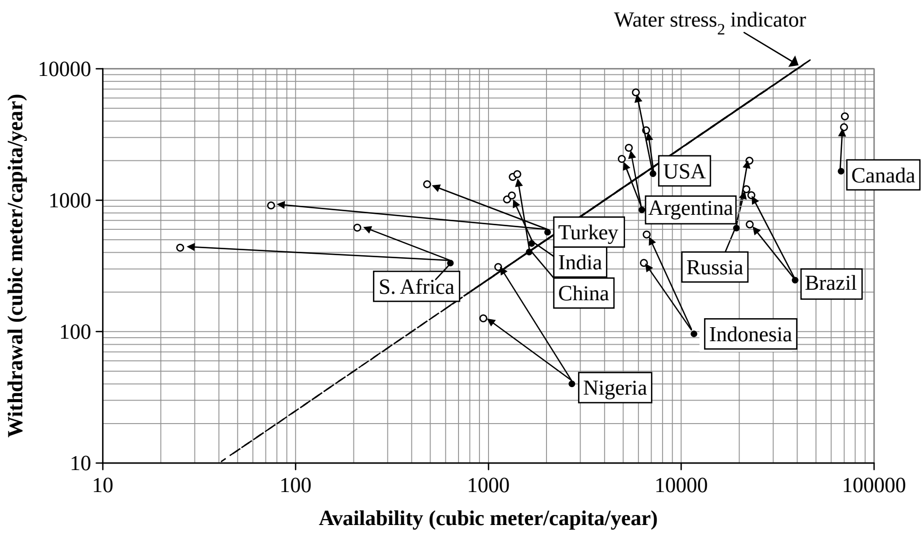

Figure 4. Per capita water withdrawal and availability for a selection of countries in the scenario. Below 500 m^3 cap^{-1} a country faces absolute water scarcity, between 500 and 1000 m^3 cap^{-1} water scarcity, and between 1000 and 1700 m^3 cap^{-1} water stress. Countries having more than 1700 m^3 cap^{-1} are classified as having sufficient water. The use-to-resource ratio is included as a dashed line representing the combinations of water withdrawal and availability that leads to a ratio of 25%. This line is designated Water stress$_2$ threshold following Raskin *et al.* (1995). *Source:* Berndes, G. (2006). The contribution of renewables to society, in: J. Dewulf & H. Van Langenhove (Eds) *Renewables Based Technology*. John Wiley & Sons Ltd. Reproduced with permission.

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

There are several assumptions that are crucial to the outcome of the scenario, primarily the WUE, share of ET supplied from irrigation, irrigation efficiency and the extent to which rain-fed energy crop production reduces downstream water availability. WUE has been put constant across regions and over time in the scenario. Thus, the purpose has not been to provide exact estimates of global ET from energy crop production. Rather, the purpose is to provide indications of the changes that can be expected.

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 illustrated, rain-fed biomass production could potentially lead to a similar impact on the national water situation, by redirecting water runoff to ET. However, the increased amount of water lost to ET is very uncertain, site specific and depends on the vegetation that was replaced.

The scenario by Alcamo *et al.* (1997) that provided the basis for construction of the scenario, defines water availability as the sum of modelled river runoff and groundwater recharge. This is a rough approximation of water availability. The projected long-term availability of water also depends on the precipitation estimates of the general circulation models used, which are generally less reliable than their temperature estimates.

Concluding Discussion

This analysis has provided a bird's-eye view of the implications of an expanding bioenergy sector on the future availability and use 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. Even though the incidence of energy crop irrigation is of crucial importance, the influence of rain-fed energy crop cultivation can also be significant in water-scarce regions. An important topic for future research is the potential for bioenergy production given the basin-scale competition for water. Analyses of the future use and availability of water can provide important insights into the basin-scale capacity to provide large amounts of biomass for energy.

It is not axiomatic that an expanding bioenergy production leads to negative consequences relative to water, land and other resources. The scenario above does not reflect suggested beneficial aspects of biomass production for energy. Through well-chosen localization, design, management and system integration, biomass plantations can offer extra environmental services that, in turn, create added value for the systems. The benefits of tree plantations for water erosion control and flood prevention are extensively documented, and afforestation of deforested watersheds can reduce sediment load in reservoirs and irrigation channels. Tree plantations, in some locations, can be used for salinity management on land subject to productivity losses due to soil salinity induced by rising water tables. Biomass production within agroforestry systems can also increase the 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. In-field soil evaporation and evaporating surface runoff can be redirected to energy crop transpiration, leading to increases in the productive use of evapotranspiration. Thus, one strategy for adaptation to water scarcity 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 to improve the quality of freshwater flows. Basin level planning could include biomass production as a land-use option with the potential for combining, for example, erosion control and flood prevention with income generation from carbon sink generation and biomass sales for energy.

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