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Bioenergy and water—the implications of large-scale bioenergy production for 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. 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

Fresh water is scarce in several regions of the world (Gleick, 1993; Postel, 1992). Humanity presently uses an estimated 26 percent of total terrestrial evapotranspiration and 54 percent of runoff that is geographically and temporally accessible (Postel et al., 1996). Analyses of the future global water situation given "business-as-usual" development indicate severe stresses on water resources and institutional systems in regions inhabited by a large part of the global population (Alcamo et al., 2000; Raskin et al., 1995; Shiklomanov, 1997). Falkenmark (1997) projects, for example, that water scarcity will make regions populated by more than half of the world's population dependent on food imports by 2025. Seckler et al. (1998) report that major shifts in world cereal grain trade can be expected as a result of increasing water scarcity in West Asia, North Africa, Indian Punjab, and the central plain of China.

Global warming—due to the enhanced greenhouse effect—and the associated climate changes may be 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 (Arnell et al., 1995; Arnell and Liu, 2001; Arnell, 1999; Kaczmarek, 1995). 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 (Vörösmarty et al., 2000). Especially, the question of how specific strategies for climate change adaptation and mitigation influence future water demands seems partly unexplored. To the best of this authors knowledge, no study has investigated how a large-scale cultivation of biomass for the substitution of fossil fuels would influence the future water demand and supply, at least not on a global/regional scale.

Yet, several authoritative organizations (e.g., IEA, IIASA, IPCC, WEC, Shell, Greenpeace, UNDP) emphasize modernized bioenergy systems 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 energy, and in the more biomass-intensive energy supply scenarios, biomass production for energy is suggested to expand during the 21st century to '*…a human use of photosynthesis that is comparable in scale to that for agriculture or forestry*' (Williams, 1994).

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

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sufficient to allow for a large-scale substitution of biomass for fossil fuels in the energy sector.

The paper is structured as follows: The prospective role of biomass in the future global energy system is discussed in Section 2, where a selection of studies of the potential contribution of biomass in the future global energy supply is presented. A selection of recent studies of the future global water use is summarized in Section 3. The water use in bioenergy feedstock production, and in biomass-based electricity generation and fuels production, is assessed in Section 4. In Section 5, an indication is made of water losses to energy crop evapotranspiration 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 evapotranspiration is compared with estimated present evapotranspiration from global cropland. The findings in Section 5 are then used in Section 6, 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 5. Water-related restrictions on bioenergy feedstock 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 prospective role of biomass in the future global energy system

Modernized bioenergy systems are suggested to be important contributors to future sustainable energy systems and to sustainable development (Kartha and Larson, 2000; Reddy et al., 1997; UNDP/WEC, 2001). Biomass is an attractive option for climate change mitigation in the energy sector because it is relatively cheap and can be used to produce electricity as well as liquid, gaseous and refined solid fuels. Certain biomass-based energy routes may even allow for *negative* greenhouse gas emissions, at least temporary. For example, if short-rotation forests are established on sparsely vegetated land, the induced increases in the average aboveground biomass stock, and sometimes also in soil carbon, would constitute a temporary carbon sink. The use of biomass as a feedstock for hydrogen production—with sequestration of the separated carbon in, e.g., oil/gas fields, deep sea, or aquifers—would allow for a combined carbon sink/energy supply option with a sink potential ultimately defined by the capacity of available sequestration alternatives.

If established on marginal/degraded land, or displacing annual agricultural crops, perennial energy grasses and short-rotation tree crops can generate benefits such as reduced erosion, reduced nutrient leaching, increased soil carbon content and increased soil productivity (Cook and Beyea, 2000; Grigal and Berguson, 1998; Kort et al., 1998; Ledin, 1998; McLaughlin and Walsh, 1998; Perttu, 1998; Ranney and Mann, 1994; Tolbert, 1998; Tuskan, 1998). The use of energy crops for wastewater treatment and phytoremediation has also received considerable attention (Aronsson and Perttu, 2001; Dushenkov et al., 1999; Hasselgren, 1998; Parameswaran, 1999; Perttu and Kowalik, 1997; Sims and Riddell-Black, 1998). Analyses of how bioenergy production systems could be located, designed and managed to generate such additional services show that the overall environmental benefits could be substantial (Börjesson, 1999a, b).

In almost all forward-looking energy scenarios, commercial bioenergy has a role in providing the world's energy (Houghton et al., 1992, 1995; IPCC, 2000). Bioenergy has a key role in contemporary strategies for increased use of renewable energy sources in the European Union (European Commission, 1997) and in the United States (The White House, 1999a, b). Energy crop production on land included in set-aside schemes to reduce the food surplus also presents an opportunity to make productive use of such land, and the conversion of excess cropland to profitable energy crop production is suggested as a path towards a phase-out of agricultural subsidies (Hall et al., 1993a). Biomass is also suggested a potential major source of energy in large developing countries such as Brazil (Carpentieri et al., 1993; Kinzig et al., 1999), China (Henderick and Williams, 2000) and India (Ravindranath and Hall, 1995; Sudha and Ravindranath, 1999).

2.1. A selection of studies of the global bioenergy potential

Many studies have analyzed the potential future contribution of biomass to the global primary energy supply. Approaches include *resource-focusing studies* that assess the physical biomass resource base that may be available for energy purposes. They can be described as inventories of potential bioenergy sources, with an evaluation of possibilities to utilize the sources for energy purposes. In these studies, food and materials demand, and land-use efficiency in agriculture and forestry, determine the land requirements for future food and materials production—and hence availability of land for energy crops production. *Demand-focusing studies* analyze the competitiveness of biomass-based electricity and biofuels, or estimate the amount of biomass required to meet certain exogenous targets on climate-neutral energy supply. They can be said to estimate the market penetration of bioenergy, given specified development of energy end-use demand and competitiveness of other energy sources. Thus, they project the likely development under certain scenario

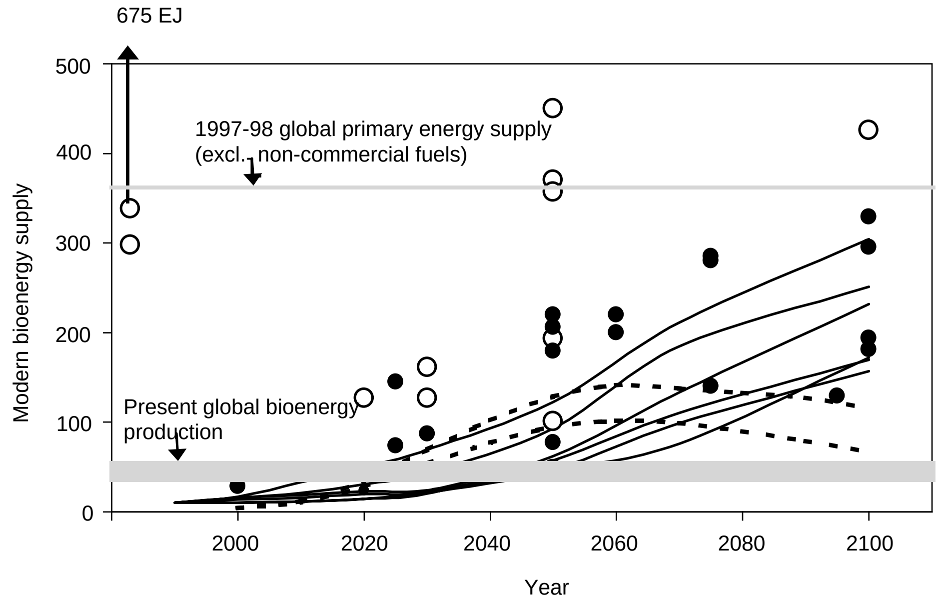

Fig. 1. The potential contribution of biomass in the future global energy supply as reported in 17 studies (adapted from Berndes et al., 2001). Hollow circles refer to resource-focusing studies and filled circles (and the solid and dashed lines) refer to demand-focusing studies. Studies that do not refer to any specific year are placed close to the *y*-axis. The present global biomass consumption for energy, which is estimated at 35–55 EJ yr^{-1} (Hall et al., 1993b; IEA, 1998; Turkenburg, 2000), and the 1997–1998 primary energy supply (excluding non-commercial fuels) of around 360 EJ yr^{-1} (BP Amoco, 1999) are included for comparison.

assumptions rather than estimate maximum physical potentials.

Fig. 1 presents the potential contribution of biomass in the future global energy supply, as reported in a selection of 17 studies. The present global biomass consumption for energy, and the 1997–1998 primary energy supply (excluding non-commercial fuels), are included for comparison. Based on a review of the studies presented in Fig. 1 (Berndes et al., 2002), it can be concluded that: (i) the future bioenergy demand (filled circles) may be 10 times as large as present biomass use for energy,[1] and (ii) the physical bioenergy potential (hollow circles) is large enough to meet this rising demand,[2] although there are diverging conclusions among the studies regarding the availability of this potential. Mainly due to different views about land availability and yield levels in energy crop production.

Most studies that differentiate between bioenergy sources predict a major role for energy crops in providing the biomass used for energy. In the studies presented in Fig. 1, up to 700 Mha is used for energy crop production in 2020–2030, up to 752 Mha is used in year 2050, and up to 1350 Mha is used in year 2100.[3] For comparison, the present extent of arable land and land under permanent crops is about 1.5 Gha, and 3.4 Gha is under permanent pasture (FAO, 2000).

Water-related restrictions on bioenergy production were not explored explicitly in any of the studies presented in Fig. 1. However, the present and projected future water situation, and the potentially large demand for water from an expanding bioenergy sector, suggest that an investigation of whether global water resources are sufficient to allow for a large-scale substitution of biomass for fossil fuels in the energy sector is warranted.

To begin with, a selection of recent studies of the present and future global water situation is presented.

[1] Especially, studies that assess bioenergy potentials as part of exploring the technical and economic feasibility of meeting low stabilization targets for atmospheric CO_2 include biomass as one of the major sources for future energy supply (see, e.g., Johansson et al., 1993; Lazarus et al., 1993; Nakicenovic et al., 1998; Williams, 1995).

[2] Among recent studies that are not included in Fig. 1 are for example the contribution of *Working Group III to the Third Assessment Report of the IPCC* (Moomaw and Moreira, 2001) that states a technical bioenergy potential in 2050 at 396 EJ per year produced from 1.28 Gha of available land, and *The World Energy Assessment* (UNDP/WEC, 2001) that states a biomass energy potential of 226–396 EJ per year from the same 1.28 Gha of available land. It is cautiously emphasized that the area requirement to support such large-scale biomass supply for energy may lead to land-use conflicts and that the water constraint for extended biomass production will likely be of importance, especially in the longer term. However, the studies do not further explore the implications of such constraints.

[3] Note that, while resource-focusing studies estimate the *availability* of land for bioenergy feedstock production based on assessments of suitable land and consideration of other land uses, demand-focusing studies estimate the *requirement* of land, given an assessed bioenergy demand, yield levels in energy crops production, and possible contribution from other bioenergy sources. The land requirement should then be interpreted as an indication of possible future land use demands arising from a growing interest in biomass use for energy.

Table 1
Present and future global water withdrawal and consumption

Study[a]	Total				Irrigation			
	Withdrawal		Consumption		Withdrawal		Consumption	
	km^3	m^3/cap	km^3	m^3/cap	km^3	m^3/cap	km^3	m^3/cap
1990s (assessments)								
Raskin et al. (1995)	2980	565			2026	384		
Alcamo et al. (2000)	3572	629			2465	434		
Shiklomanov (1997)	3760	681	2275	412	2503	453	1952	354
Postel et al. (1996)	4430	856	2285	441	2880	556	1870	361
2025 (forecast/scenario)								
VAL scenario (Alcamo et al., 2000)	2593	348			1971	264		
TEC scenario (Alcamo et al., 2000)	3412	432			2559	324		
BAU scenario (Alcamo et al., 2000)	4092	510			2292	285		
CDS scenario (Raskin et al., 1995)	3700	441			2115	252		
Forecast (Shiklomanov, 1997)	5187	626	2879	348	3162	382	2377	287
Forecast (Postel, 1998)								
2050 (scenario)								
CDS scenario (Raskin et al., 1995)	4300	427			2180	216		

[a] Conventional development scenario (CDS), business-as-usual (BAU), technology, economics, and private sector (TEC), values and lifestyles (VAL).

3. Overview of recent analyses of the present and future global water situation

Table 1 presents the results of a selection of studies assessing present and future global water use. The water use data in Table 1 refers to water use that requires that water is withdrawn from its original location. The part of withdrawn water that evaporates due to its withdrawal is referred to as consumed water. Irrigation presently accounts for an estimated 65–70 percent of total withdrawals. The irrigation share of consumptive water use is even higher: 80–85 percent according to the two studies that include estimates of present water consumption.

Water withdrawals can be distinguished from in-stream water use, such as shipping, fishing and pollution dilution, which is not included in Table 1. Postel et al. (1996) estimated, for example, the global pollution dilution requirement to 2350 km^3 for the year 1990, which is almost as large as the assessed water withdrawals in the 1990s.

Forecasts, or scenarios, of future water withdrawals are based on present trends for important driving forces, and on assumptions about how they will change in the future. Population growth and economic development are basic driving forces. They are combined with specific factors (e.g., domestic water use per capita, industrial water use per industrial GDP) in order to calculate the sectoral water withdrawals. The factors change over time according to assumptions about how per-capita water use changes with economic development and lifestyles. Assumptions about changes in irrigated area and in irrigation water use per hectare are crucial for the total withdrawals since irrigation is the major source behind water withdrawals.

The BAU scenario, the CDS scenario, and the two forecasts in Table 1, project future water withdrawal and consumption given that present trends in population, economic development, technology and lifestyles prevail over the scenario period (business-as-usual). The normative VAL and TEC scenarios by Alcamo et al. (2000) explore possibilities for water conservation and deep reductions in the intensity of water use.

Global population and per-capita water withdrawals from 1900 to 1990 are given in Fig. 2, together with projections for year 2025 that are summarized in Table 1. The graphs refer to the total and sectoral global water withdrawals from 1900 to 1990, complemented with forecasts up to year 2025 by Shiklomanov (1997). Global water withdrawals reported for year 2025 in the studies by Alcamo et al. (2000) and Raskin et al. (1995) are included as filled dots in the figure.

Per-capita withdrawals in agriculture (mainly irrigation) almost tripled from 1900 to 1960, but came to a turning point between 1960 and 1970 and have decreased since. Total agricultural withdrawals have increased about 60 percent since 1960, but this growth is smaller than the population growth. The global population has approximately doubled since 1960. The projections differ in their view of future agricultural withdrawals, mainly due to differing views about the prospects for an expansion of irrigated land. Irrigated land expansion up to 2025 ranges from 1.5 percent in the BAU scenario by Alcamo et al. (2000) to 35 percent in the forecast by Shiklomanov (1997). All studies expect that per-capita agricultural withdrawals will continue to

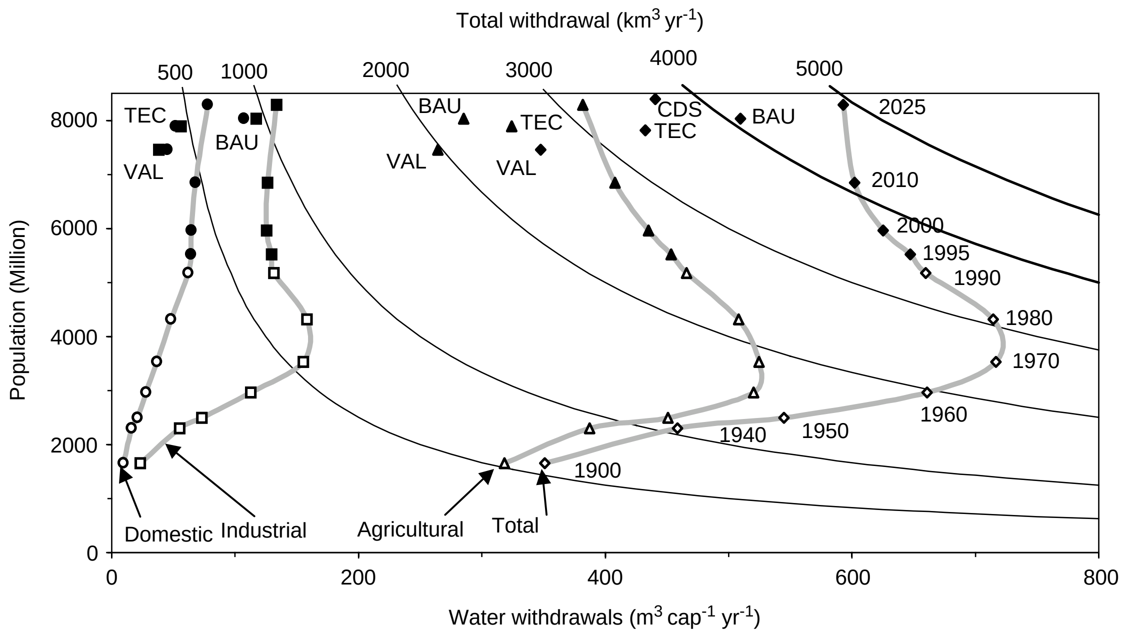

Fig. 2. Historic and projected future total and sectoral withdrawal. Hollow symbols refer to assessments, and filled symbols refer to forecasts or scenarios. Triangles refer to the agricultural sector, circles refer to the domestic sector, squares refer to the industrial sector, and diamonds refer to total water withdrawals. The graphs refer to assessed total and sectoral water withdrawals from 1900 to 1990, complemented with forecasts up to 2025 (Shiklomanov, 1997). The thin lines represent combinations of per-capita withdrawals and population sizes that result in the total withdrawals that are indicated for each thin line in the top of the figure.

decrease up to 2025, but the total agricultural withdrawals increase in four cases and decrease in two cases.

Per-capita industrial withdrawals increased up to 1980 and then declined to about 80 percent of the 1980 level in 1990. The present total industrial withdrawals are almost 20 times larger than in 1900, and it is around four times larger than the 1950 level. The business-as-usual cases report industrial withdrawals in 2025 about 25–60 percent larger than the 1990 level. The two normative VAL and TEC on the other hand suggest that the industrial withdrawals could be reduced to about 40 and 60 percent of the 1995 level, from accelerated improvement in water use efficiency (WUE) and shifts to non-thermal power plants and non-water intensive industries.

Per-capita domestic withdrawals have increased steadily since year 1900. The 1990 per-capita domestic withdrawals are more than six times larger than the 1900 level and almost three times the 1950 level. The 1990 total domestic withdrawals are more than 20 times the 1900 level and about 6 times the 1950 level. The business-as-usual cases report a continuing growth in per-capita domestic withdrawals, which together with population growth leads to a total domestic withdrawal in 2025 that is about 2–2.5 times the 1990 level. The VAL and TEC scenarios suggest that the 2025 domestic withdrawals could be kept approximately at the 1990 level, thanks to reductions in the per-capita domestic withdrawal.

To summarize, irrigation has dominated global water withdrawals and is expected to continue to do so. The growth in agricultural withdrawals will continue to be lower than population growth, leading to decreasing per-capita agricultural withdrawals. The extent of irrigated land is crucial for the future agricultural withdrawals, and different views exist about the prospects for an expansion of irrigated land. Continued growth in per-capita withdrawals in the domestic and industrial sectors will, in combination with population growth, lead to substantial increases in water withdrawals in these sectors unless important breaks in present trends are achieved. The normative VAL and TEC scenarios illustrate how improvements in the WUE and shifts to less water intensive economic activities can lead to such breaks.

One main conclusion from this review of water studies is that *no study includes large-scale energy crops production as a new source of water demand in the future*. Projected irrigation water withdrawals relate to demand in the food sector, which is determined by population size and factors such as diet and mix of food crops under irrigation. Energy sector withdrawals are dominated by thermoelectric withdrawals. In addition to energy demand, the prospects for a transition from water-cooled thermoelectric generation to alternative technologies that use water sparingly is regarded crucial for trends in energy sector withdrawals.

In order to indicate whether global water resources are sufficient to allow for a large-scale substitution of biomass for fossil fuels, the scenarios of future global water withdrawals need to be complemented with estimates of how much additional water that might be required to operate a bioenergy system of a size envisioned in the more biomass-intensive energy scenarios discussed in Section 2.1 earlier.

First, the amount of water that is required to grow biomass and convert it to biofuels or electricity is estimated. The water requirements of large-scale bioenergy production are then estimated and compared with other water requirements and with estimates of future water availability.

4. The water requirements in energy crop production and in biomass-based electricity and fuel production

4.1. Water requirements in energy crop production

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. The concept 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.

Water evapotranspiration in energy crop production is given for different bioenergy systems in Table 2. There are several contributing factors behind the wide ranges in this table.

First, the WUE varies among crop types. A distinction can be made between C_3 and C_4 crops, where C_4 crops generally have a higher WUE and productivity than C_3 crops (Black and Ong, 2000; Loomis and Connor, 1992). The WUE of a specific crop also vary with climate, growing period and agronomic practice (Allen et al., 1998), and there are several options for modification of the WUE (e.g., changing sowing date and plant density, supplemental irrigation and microclimate manipulation). The range given for the WUE in Table 2 comprise the data found in a literature survey (Berndes and Börjesson, 2001). The extraordinary high upper bound given for lignocellulosic crops correspond to cultivation of *Miscanthus giganteus* (C_4 plant) in southeast England (Beale et al., 1999). Similar to exceptionally high biomass yields sometimes reported from field trails, such WUE data illustrate what can be reached under favorable conditions, but they are hardly representative of average WUE that could be achieved over large areas around the world.

Second, the share of the aboveground biomass that is usable as feedstock in the production of fuels or in generation of electricity varies between crops and conversion technologies. Present practice in ethanol production based on traditional food crops can be used as an illustrative example. When ethanol is produced from sugarcane or sugarbeet, only the sugar in the crops is used as feedstock. When it is produced from cereals such as wheat or corn, only the starch-rich grain is used. On a dry matter (DM) basis, about 25 percent of aboveground sugarcane growth, and about 40 percent of sugar beet whole-plant mass, is sugar (Cooke and Scott, 1993; Muchow et al., 1996a, b; Wirsenius, 2000). The ratio of grain to total aboveground DM varies significantly among cereals, but it is usually below 0.5 (Wirsenius, 2000). Thus, less than half of aboveground growth is usable as feedstock when ethanol is produced from sugarcrops 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 biofuel substantially.[4]

Third, there are different technology options available for biofuel production and electricity generation, and the conversion efficiency varies substantially among the options. Note that data in Table 2 for lignocellulose-based ethanol, methanol and hydrogen production are based on laboratory experience and expected performance in large-scale plants as production of such fuels from biomass is not yet commercialized. This also applies for electricity generation using integrated gasification/gas turbine technologies, which represent the high-efficiency case in Table 2. However, several processing steps are similar to those already available for coal or natural gas. Biomass gasification technologies are being developed based on existing technologies for coal gasification, gas turbine technologies for prospective biomass-based electricity generation are those used for fossil electricity, and the post-gasification technologies for methanol and hydrogen production are the same as those using natural gas as a feedstock. Similarly, lignocellulose-based ethanol production can draw on experience from ethanol production based on, for example, corn and sugarcane.

[4] 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 what is needed in the factory. System designs that combine ethanol production with off-season electricity generation can export almost 600 kWh electricity and 85 l ethanol per Mg cane processed (Larson and Kartha, 2000; Macedo, 1998).

Table 2
Energy crop evapotranspiration per unit bioenergy feedstock production and per unit gross bioenergy production. Based on Berndes and Börjesson (2001)

Biofuel/feedstock	Water use efficiency[a] (kg DM ha^{-1} mm^{-1} ET)	Energy crop evapotranspiration[b]	
		(Mg GJ^{-1} feedstock[c])	(Mg GJ^{-1} gross bioenergy[d])
Biodiesel			
Rapeseed	9–12	46–81	100–175
Ethanol			
Sugarcane	17–33	23–124	37[e]–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[f]		
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 1 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 Berndes and Börjesson (2001) for original references.

[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.

[c] The primary feedstock shares of total aboveground dm production are: 0.5 for rapeseed (Beiwinga and van der Bijl, 1996); corn 0.4 (Wirsenius, 2000); wheat 0.45 (Wirsenius, 2000); sugarcane 0.27 (sugar content is 45 percent of stalk dm (Muchow et al., 1996a, b; Wirsenius, 2000), stalk dm is 60 percent of total aboveground cane dm (Wirsenius, 2000)); sugar beet 0.42 (sugar content is 70 percent of beet dm (Cooke and Scott, 1993; Wirsenius, 2000), beet dm is 60 percent of whole-crop dm production (Wirsenius, 2000)); and lignocellulosic crops 0.8 (Ercoli et al., 1999; Madakadze et al., 1998; Nonhebel, 1995).

[d] 370 l RME Mg^{-1} rapeseed (Lysen et al., 1992; Peterson and Hustrulid, 1998); 440 l ethanol Mg^{-1} corn grain (Shapouri et al., 1995; Wyman et al., 1993); 450 l Mg^{-1} wheat grain (IEA, 1994; Lysen et al., 1992); 600 l Mg^{-1} cane (Macedo, 1998) or beet sugar (Beiwinga and van der Bijl, 1996; IEA, 1994). Lignocellulosic crops: ethanol, low = 40 percent (high: 54 + 11 percent electricity) of feedstock hhv (Lynd, 1996; Wyman et al., 1993); methanol, low = 50 percent (high: 70 percent) (Williams et al., 1995); hydrogen, low = 55 percent (high: 70 percent) (Williams et al., 1995); and electricity, low = 35 percent (high: 55 percent) of feedstock hhv. Biomass-fueled steam power plants, operating at efficiencies as low as 15–20 percent require (i) low cost feedstocks (such as waste), (ii) additional sale of heat (co-generation), or (iii) special policy incentives in order to be economically feasible (Bain et al., 1998; Gustavsson and Börjesson, 1998; Williams and Larson, 1993, 1996).

[e] Cane-ethanol system design including steam conservation, BIG/ISTIG electricity generation using bagasse during milling season, and tops and leaves during off-season. Electricity generation in excess of onsite needs is 286 kWh Mg^{-1} fresh stalk during 160-day milling season, and 435 kWh Mg^{-1} fresh stalk during off-season: average 370 kWh Mg^{-1} fresh stalk (Ogden et al., 1990).

[f] The high value refers to rain-fed *Miscanthus giganteus* in southeast England (Beale et al., 1999).

The lower bound data for energy crop evapotranspiration in Table 2 combine the highest WUE data with systems 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 2 combine the lowest WUE data with systems with lower conversion efficiency that do not use harvest residues or process by-products for energy.

Note that water use in the production of biofuels or in generation of electricity is not included in Table 2. The consumptive water use in biomass-based fuel production and electricity generation is low compared to evapotranspiration in energy crop production, as will be shown in the next section.

4.2. Water requirements in biomass-based electricity and fuel production

Biomass contains water. When biomass is used for energy, most of this water is lost to evaporation during pre- and post-harvest drying, pre-treatment, combustion, gasification, and fuel processing. However, the amount of water that is evaporated this way is small compared to evapotranspiration losses during growth. If, for example, biomass is harvested, dried, and combusted for electricity generation at 25 percent efficiency, a moisture content of 50 percent in fresh biomass corresponds to about 0.2 Mg water per GJ electricity generated.[5] This is roughly a

[5] A higher heating value (HHV) of 20 GJ Mg^{-1} DM biomass is used throughout this paper.

Table 3
Indicative data on water requirements in biomass-based fuel production and electricity generation

Bioenergy option	$Mg\,GJ^{-1}$ gross bioenergy[a]	$g\,g^{-1}$ DM feedstock
Electricity generation		
Total thermoelectric generation in USA 1995[b]	30 (withdrawal) 0.5 (evaporation)	
Biomass-based steam plants constructed in USA in the mid-1980s[c]	0.7[d]	3
Improved biomass-based steam plant[c]	0.5[e]	3.6
Gasification-based biomass electricity[f]	0.1[g]	0.6
Fluid biofuels		
Hydrogen, gasification, shift reaction and reforming[h]	0.1-0.3[i]	1–4
Methanol, gasification, shift reaction and reforming[j]	0.05–0.1	0.5–1.5
Quench feed water for wet scrubbing of syngas exiting biomass gasifier[k]	0.03–0.9 (methanol) 0.2–4.6 (hydrogen)	
Ethanol based on pine, process water[l]	0.1–6.5[m]	1–34
Ethanol production, stillage yield[n]	0.5 (beet molasses) 0.7 (cane juice) 0.6 (cane molasses) 0.5 (cellulosics)	

[a] HHV basis.
[b] All fuels. Withdrawals for condenser cooling dominates. Only a small share of this water is evaporated (Solley et al., 1998).
[c] Power plant water requirements (USDOE/EPRI, 1997).
[d] Calculated based on the specified efficiency of 23 percent and assuming a HHV at $20\,GJ\,Mg^{-1}$.
[e] Calculated based on the specified efficiency of 34 percent and assuming a HHV at $20\,GJ\,Mg^{-1}$.
[f] Boiler feed water requirements in a biomass gasification combined cycle system where steam from the steam cycle is injected into the gasifier (USDOE/EPRI, 1997). Wet scrubbing would lead to additional water requirements.
[g] Calculated based on the specified efficiency of 36 percent and assuming a HHV at $20\,GJ\,Mg^{-1}$.
[h] Mann (1995), and Williams et al. (1995).
[i] Higher number includes steam for electricity or heat export.
[j] Williams et al. (1995).
[k] Katofsky (1993).
[l] von Sivers and Zacchi (1993).
[m] Higher and lower numbers refer to dilute and concentrated hydrochloric acid process, respectively. Process water requirements for the enzymatic hydrolysis process are around $3\,Mg\,GJ^{-1}$ ethanol. Additional outputs such as lignin fuel and methane from anaerobic digestion are not considered in the table.
[n] Average of 3, 2, 7, 4 cases for beet molasses, cane juice, cane molasses, and cellulosics, respectively (Wilkie et al., 2000).

factor 50 or more below the estimated energy crop evapotranspiration per GJ biofuel/electricity, presented in Table 2.

Table 3 presents data for the water requirements in biomass-based fuel production and electricity generation. Due to the uncertainties involved in assessing prospective technologies, the numbers in Table 3 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. Ethanol production can, for example, generate additional outputs such as methane, lignin fuel, electricity, and also animal feed and by-products such as furfural, which has potential use for production of new polymers (Kaylen et al., 2000; Larson and Kartha, 2000; Lynd, 1996).

4.2.1. Electricity generation

Thermoelectric generation is one of the dominating factors behind water withdrawals in industrialized countries. Most of the withdrawn water is used in the condenser to cool steam back into water. The condensed water is pumped back to the boiler to become steam again, while the cooling water—which is separate from the boiling water/steam—is either returned directly to water bodies after use (once-through cooling), or sent to cooling towers or ponds from which it can be recycled or returned to water bodies at a lowered temperature. The water withdrawals are reduced when recycling in cooling towers or ponds is employed, but a higher share of the cooling water (usually more than 60 percent (Solley et al., 1998)) is evaporated in such systems.[6] Hybrid wet/dry condensers and air-cooled condensers allow for very low water requirements, with consumptive water use two orders of magnitude lower than for cooling tower systems (Hughes, 1998).

Besides for cooling, water is withdrawn to replace the water lost due to steam venting, and also for blowdown

[6] For example, Gleick (1994) estimates that nearly 0.5 Mg water is evaporated per GJ of coal in a coal-fired power plant using once-through cooling, while water evaporation at a plant using cooling towers is estimated to be more than two times higher: about 1 Mg per GJ of coal, or about 10 Mg per MWh_e ($3\,Mg/GJ_e$) at 35 percent electricity generation efficiency.

(cleaning) of boilers, washing of stacks and for employee and plant sanitation.[7] However, most of the water used in today's thermoelectric plants is cooling water and only a small share of this is lost to evaporation. For example, only about 2 percent of withdrawals, or 0.5 Mg per GJ_e, were lost to evaporation in thermoelectric plants in USA 1995 (Solley et al., 1998). This is similar to the estimated power plant water requirements at commercially available biomass-fired steam plants constructed in the mid-1980s in USA, which are about 0.2 Mg per GJ biomass, or 0.7 Mg per GJ_e at the specified efficiency of 23 percent (USDOE/EPRI, 1997).

Among the prospective technologies for biomass-based electricity generation, biomass integrated-gasification/gas turbine (BIG/GT) systems stand out due to potentially favorable economics at intermediate scales and prospects for near-term commercialization (Consonni and Larson, 1996). In such systems, the biomass is dried, thermochemically converted to a gaseous fuel, cleaned from contaminants, and fired in a gas turbine for electricity generation. The recovery of waste heat from the gas turbine exhaust leads to higher efficiency, and several cycle options have been proposed.[8]

BIG/GT systems use water (i) in feedstock gasification when steam is injected to promote gasification reactions and act as fluidizing agent; (ii) in syngas cleaning if wet-quench cleanup (scrubbing) is used, and, depending on configuration, (iii) for condenser cooling, or to produce steam for process heat cogeneration or injection into the gas turbine.

Gasifier steam input varies with gasifier design. Reported range corresponds to 0.002–0.2 Mg water per GJ_e at 40 percent electricity generation efficiency (Mann, 1995; Williams et al., 1995). Only a small fraction of the injected steam is consumed in the gasification reactions, and recycled product gases can potentially substitute for some of the water used in the gasifier design corresponding to the upper range value above. Compared to coal gasification, only about 40 percent as much high-pressure steam is required to gasify 1 GJ of biomass as 1 GJ of coal. Furthermore, some low-pressure steam needed for the sulfur recovery with coal is not needed in the biomass system (Williams and Larson, 1993).

The syngas exiting the gasifier needs to be cleaned from contaminants such as particulates and alkali metals, which can damage turbine blades. Water input in wet scrubbing varies significantly with scrubber type (Ebert and Büttner, 1996), but can be much larger than the input of makeup water for gasification (Katofsky, 1993). The use of wet scrubbing can be expected to lead to additional wastewater treatment rather than substantial increases in consumptive water use as evaporation. Dry technologies for hot-gas clean-up save water and improve the efficiency (Bain et al., 1998; Williams and Larson, 1993). High temperature filters allow removal of particulates and alkali compounds without lowering the temperature below the dew point of tars and oils, so that they can be burned in the gas turbine combustor and further improve the efficiency.

Steam-injected gas turbines can be expected to have a higher consumptive water use than turbines without steam injection, since steam that is injected into a gas turbine is not re-captured as it is in a steam cycle. Thus, while water losses as evaporation are inherent in water or steam-injected cycles, the combined cycle option (as the traditional steam turbine plant) has the advantage of potentially low water demand thanks to possibilities to use hybrid wet/dry condensers and air-cooled condensers.

4.2.2. Biofuel production

As for BIG/GT electricity systems, biomass-based methanol and hydrogen production starts with thermochemical gasification of biomass, although there are different synthesis gas requirements when methanol or hydrogen is the end product. Depending on process configuration, additional water may be required in shift and reforming reactors. Mann (1995) estimated total water use in hydrogen production (based on hot-gas clean-up processes) to around 0.3 Mg per GJ hydrogen, with more than 70 percent being export steam generated from excess heat from the reforming operation. This steam substitutes for other steam generation—and hence water use—when sold. Williams et al. (1995) report that 0.07–0.1 Mg water is used per GJ hydrogen, but include only steam generated for the process. Similar values are reported for methanol production.

If wet scrubbing of the syngas is employed, the quench feed water supply is usually larger than the makeup water supply to gasification, water-shift and reforming reactors. Detailed process simulations (Katofsky, 1993) imply quench feed water supply ranging from 0.03 to 0.9 Mg per GJ methanol and 0.2–4.6 Mg per GJ hydrogen. As mentioned earlier, the use of wet scrubbing leads to additional wastewater treatment but not necessarily to substantial increases in evaporation.

Ethanol is fermented from sugars and is concentrated from the fermentation mixture for further processing or direct use as a fuel. The water not recycled to the process is obtained as stillage that requires treatment before it can be reused or returned to water bodies. Wash water from fermenter cleaning, as well as cooling water blow

[7] In nuclear plants, water is also used to keep the nuclear fuel from overheating and melting.

[8] Among the configurations that have recieved attention recently are (i) combined cycles (CC) where the waste heat is used to generate steam for additional power in a steam turbine; (ii) Steam-injected gas turbines (STIG) where generated steam is injected into the gas turbine combustor for increased power output and electrical efficiency, and (iii) intercooled CC and STIG where intercooling between compressor stages reduces compressor work and also allows for higher turbine inlet temperature due to the improved air cooling of turbine blades.

down and boiling water blow down, may be combined with stillage and contribute to total effluent production. Treatment can involve anaerobic fermentation with methane recovery. Alternative management involves for example using stillage as fertilizer, or concentrating it for use as animal feed.

The water requirements for ethanol production reported in Table 3 relate to either stated process water requirements for specific ethanol production processes, or the stillage yield from ethanol plants. The stillage yield can be considered indicative of water withdrawals in an ethanol plant. In reality water withdrawals are likely to be somewhat lower since several treatment methods facilitate recycling of part of the stillage water. Also, some of the water in the stillage have entered the ethanol plant with the feedstock. Complete water recycling in the ethanol production process is presently prevented from incomplete separation of low molecule weight organic substances and build-up of inhibitors (Cartwright, 1992). Non-recycled water may substitute for other water, e.g., when used for irrigation.

The impact from ethanol production on water resources does not primarily relate to evaporation losses or water consumption in chemical reactions, but to the potential pollution load on aquatic systems (Frings et al., 1992; Giampietro et al., 1997). However, according to a recent technical evaluation of stillage characterization, treatment, and by-product recovery in the ethanol industry (Wilkie et al., 2000), sustainable and economically viable solutions are available for mitigating the environmental impacts which results from large-scale ethanol plants.

To summarize, the consumptive water use (through evaporation or chemical reactions) for biomass-based electricity generation depends on system configuration. Electricity generation based on biomass and nuclear/fossil fuels involves several similar basic steps, and the change in specific water consumption due to a fuel shift from nuclear or fossil fuels to biomass depends on the induced technology choices rather than the fuel shift per se.[9] 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 focus is on energy crops production since this was identified as the major source of consumptive water use in bioenergy production.

[9] Although, the water losses from evaporating the moisture in biomass can make up a significant part of total water losses in configurations having very low consumptive water use.

5. Evapotranspiration from large-scale energy crop production

A comparison of evapotranspiration from large-scale energy crop production with other human appropriation of evapotranspiration can give perspectives on bioenergy production at the scales suggested in the more biomass-intensive scenarios of future energy use and supply. For this purpose, the six IIASA/WEC scenarios developed by the International Institute for Applied Systems Analysis (IIASA) and the World Energy Council (WEC) (Nakicenovic et al., 1998) will be used as examples of how the future biomass supply for energy could develop. 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 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.

Lignocellulosic crops are expected to be the major source of biomass for energy in the future. The analysis of the water implication of large-scale bioenergy production will therefore assume that such crops are cultivated to provide the feedstock for electricity and biofuel production. The global average energy crop evapotranspiration will be 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 2 (1–9.5 g DM per kg water). But, as was mentioned earlier, a WUE of 9.5 g DM per kg water is exceptionally high. Kinzig et al. (1999) 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.

Fig. 3 presents the evapotranspiration from energy crop production in the IIASA/WEC scenarios, given that plantations provide the total biomass supply for energy. The energy crop evapotranspiration will be lower if residues and process by-products from the food and forest sector provide a share of the biomass supply for energy.[10] If, for example, 25 percent of biomass

[10] Nakicenovic et al. (1998) estimated the land use requirements of the two most biomass-intensive scenarios A2 and A3 in a post-scenario feasibility test. Lower bound estimates assumed that 80 percent (2050) and 67 percent (2100) of biomass was produced from plantations. Higher bounds assumed 100 percent plantations.

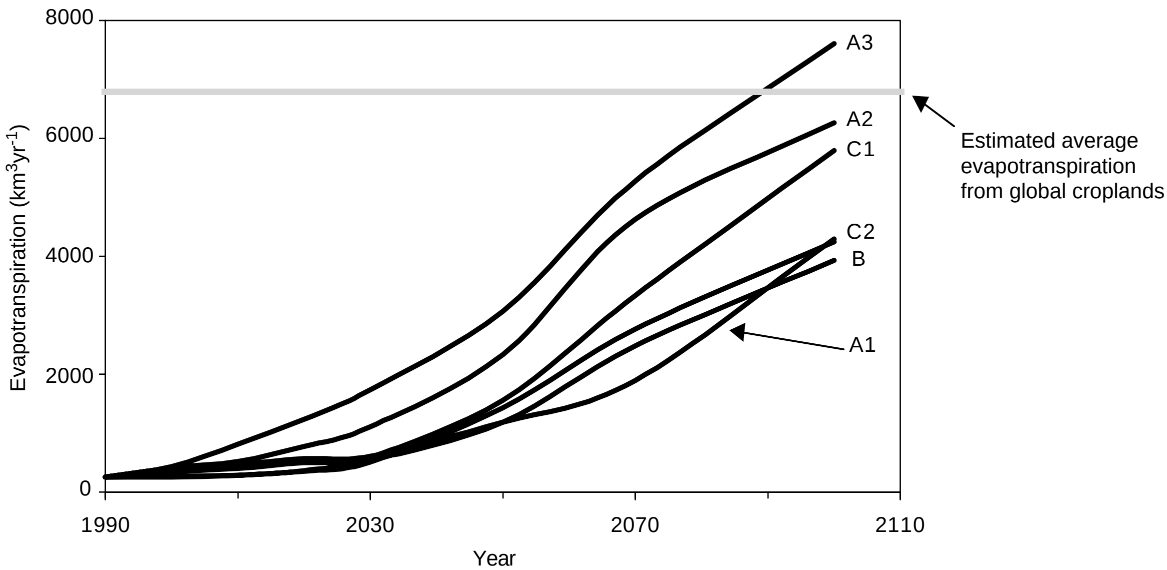

Fig. 3. Evapotranspiration from energy crops production in the IIASA/WEC scenarios, and estimated evapotranspiration from global cropland. See text for assumptions.

supply for energy were provided from residues, then the curves in Fig. 3 would be 25 percent lower.

The estimated present global cropland evapotranspiration is included in Fig. 3 as a comparison (Rockström et al., 1999). The reported cropland evapotranspiration, $6800\,km^3\,yr^{-1}$, is based on a detailed bottom-up calculation of the evapotranspiration from all major food crops. The calculation includes evapotranspiration from weeds and vegetation in open drainage ditches, green enclosures, and wind breaks. Two other estimates of global cropland evapotranspiration ($3200\,km^3\,yr^{-1}$ (Postel, 1998) and $7500\,km^3\,yr^{-1}$ (Postel et al., 1996)) are based on more rough approaches and judged less reliable.

Fig. 3 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 that from present global crop production.

It was shown in Section 4.1 that the WUE vary significantly. It is easy to imagine WUE levels that are a factor of two higher or lower. The graphs in Fig. 3 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 studies of future water use that was reviewed in Section 3 did not include energy crops irrigation in their estimates of future agricultural water withdrawals. 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. A comparison of these numbers with the irrigation withdrawal estimates presented in Section 3 clearly shows that such additional withdrawals would lead to substantial increases in total withdrawals.

In the following section, 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. The resulting future water requirements and availability are analyzed based on two frequently used indicators.

6. A scenario of future water use and availability

6.1. Scenario construction and some tentative conclusions

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 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 conversion 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 (Evans, 1992). 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, corresponding to 30 percent[11] of the evapotranspiration from each country's energy crop production, increasing the withdrawals 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.
- 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* (Falkenmark, 1989; Raskin et al., 1995) 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 Raskin et al. (1995).

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 (Allan, 1998; Bouwer, 2000; Wichelns, 2001). 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. (1996) 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 (Postel et al., 1996).

The scenario construction does not capture suggested water-related beneficial aspects of bioenergy feedstock production. The use of energy crops for wastewater treatment has already been mentioned. 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 (Evans, 1992). 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.[12] 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 (Ong et al., 1992). In-field soil evaporation and evaporating surface runoff can be redirected to energy crop transpiration, leading to increases in the productive use of evapotranspiration.[13] 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.

Fig. 4 shows the results for a selection of countries (the results for 42 countries—covering about three-fourth of total land area, and having almost 90 percent of global arable land and land under permanent crops—are found in the appendix). Filled dots represent the present situation. Two arrows originate from each dot, where the one moving furthest towards the *y*-axis

[11] As in Section 5, irrigation withdrawals are assumed to supply water corresponding to 15 percent of evapotranspiration from energy crop production, with an irrigation efficiency of 50 percent.

[12] Although, the efficiency and long-term sustainability of such approaches to salinity management are subject to discussion. See, e.g., George et al. (1999), and Heuperman, (1999).

[13] Trees in agroforestry systems may improve microclimate 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 understory crops vary (Black and Ong, 2000; Kho, 2000; Ong et al., 2000). The net *income generation* effect of establishing agroforestry systems depend on the relative values of potential carbon sinks, wood harvest and crop harvest.

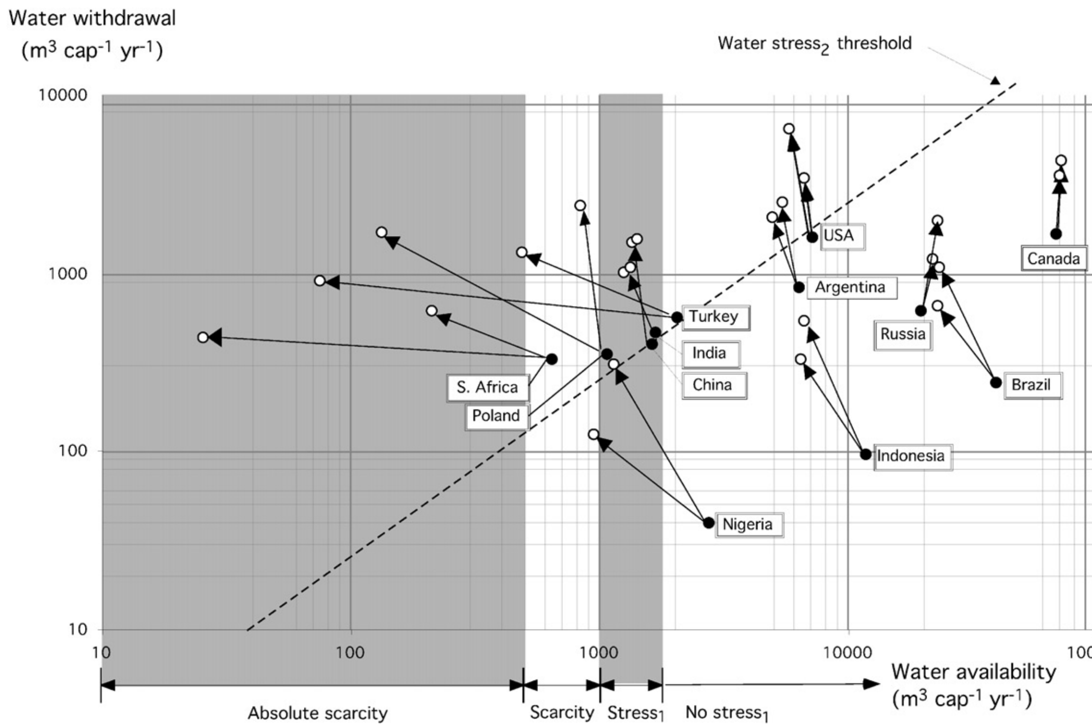

Fig. 4. Per-capita water withdrawal and availability for a selection of countries in the scenario. Filled dots represent the situation in 1995. The two arrows that originate from each dot point to the situation in year 2075, according to the two scenario variants. The arrow that point farthest to the *y*-axis represent the zero energy crop irrigation case. The impact of rain-fed energy crop production is here modeled as a redirection of runoff to energy crop evapotranspiration (and hence, reduced water availability). The other arrow represent the irrigation case, where 15 percent of the water that is lost to energy crop evapotranspiration are assumed to be supplied by means of irrigation (with average irrigation efficiency of 50 percent). 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.

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 use 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:

- 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.

6.2. Sensitivity with respect to critical assumptions

There are several assumptions that are crucial for the outcome of this scenario, primarily the WUE, share of evapotranspiration supplied from irrigation, irrigation efficiency, and the extent to which rain-fed energy crops 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 evapotranspiration from energy crops production. Rather, the purpose is to provide indications of the changes that can be expected. It is easy to imagine WUE 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 percent assumptions are largely arbitrary, and doubling the 15 percent assumption would double the water use levels. As have been illustrated, rain-fed 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 biomass energy 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 (Alcamo et al., 1997).

Major rivers flow through areas remote from population centers, and a long distance from potential cropland (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 (Alcamo et al., 1997).

7. 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.

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Appendix

This appendix presents the result of the scenario of future water use and availability. Country-specific results are given for 42 countries. Some basic data on land use and irrigation are also included. Together, the countries cover about three-fourth of total land area, and almost 90 percent of global arable land and land under permanent crops. The countries are grouped according to the regionalization in the IIASA/WEC study (Nakicenovic et al., 1998). See Section 6.1 for information about the scenario construction (Table A1).

References

Alcamo, J., Döll, P., Kaspar, F., Siebert, S., 1997. Global change and global scenarios of water use and availability: an application of WaterGAP 1.0. Center for Environmental Systems Research (CESR), University of Kassel, Germany.

Alcamo, J., Henrichs, T., Rösch, T., 2000. World water in 2025—global modeling and scenario analysis for the World Commission on Water for the 21st Century. Center for Environmental Systems Research, University of Kassel, Kurt Wolters Strasse 3, 34109 Kassel, Germany.

Allan, J.A., 1998. Virtual water: a strategic resource. Global solutions to regional deficits. Ground Water 36 (4), 545–546.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration: Guidelines for computing crop water

Table A1

Region/country	Land & irrigation			1995			2075 Energy crop irrigation scenario			2075 Zero irrigation scenario		
	Total land area (Mha)	Arable land and permanent crops (Mha)	Percent of arable land and permanent crops irrigated	Water withdrawal ($m^3 cap^{-1} yr^{-1}$)	Water availability ($m^3 cap^{-1} yr^{-1}$)	Use-to-resource ratio (percent)	Water withdrawal ($m^3 cap^{-1} yr^{-1}$)	Water availability ($m^3 cap^{-1} yr^{-1}$)	Use-to-resource ratio (percent)	Water withdrawal ($m^3 cap^{-1} yr^{-1}$)	Water availability ($m^3 cap^{-1} yr^{-1}$)	Use-to-resource ratio (percent)
North America												
USA	936	179	12	1591	7155	22	3396	6590	129	2637	5831	140
Canada	997	46	2	1657	67551	2	4339	70733	6	3580	69974	5
Former Soviet Union												
Russian Fed	1708	128	4	612	19363	3	1995	22575	9	1210	21790	6
Ukraine	60	34	7	549	2289	24	1815	1820	100	1030	1035	100
Kazakhstan*	272	31	7	2541	8333	30	4801	8851	120	4016	8066	124
Belarus	21	6	2	250	5974	4	1275	5169	25	490	4384	11
Pacific OECD												
Australia	774	51	5	667	19125	3	653	16821	4	638	16806	4
Japan	38	5	55	777	2128	37	1414	2287	62	1399	2272	62
Centrally planned Asia and China												
China	960	135	38	403	1627	25	1578	1413	112	1504	1339	112
Viet Nam	33	7	43	422	2956	14	1537	2329	66	1463	2255	65
South Asia												
India	329	170	33	467	1677	28	1084	1323	82	1011	1250	81
Pakistan*	80	22	81	1273	221	576	1610	438	368	1537	365	422
Bangladesh*	14	8	44	189	1464	13	235	971	24	162	898	18
Afghanistan	65	8	30	1469	2106	70	628	771	82	555	698	80
Other Pacific Asia												
Indonesia	190	31	15	96	11646	1	547	6622	8	333	6408	5
Thailand*	51	20	23	606	4910	12	968	3038	32	754	2824	27
Myanmar	68	10	15	71	13568	1	307	9181	3	93	8967	1
Philippines	30	10	16	584	3009	19	2501	1619	154	2287	1405	163
Malaysia	33	8	5	765	28735	3	2111	15873	13	1897	15659	12
Sub-Saharan Africa												
Nigeria	92	31	1	40	2712	1	310	1125	28	126	941	13
South Africa	122	16	8	332	636	52	618	209	296	434	25	1723
Ethiopia	110	11	2	40	1732	2	251	1099	23	67	915	7
Congo, Dem R*	234	8	0.1	124	33925	0	312	10250	3	128	10066	1

Table A1 (*continued*)

Region/country	Land & irrigation			1995			2075 Energy crop irrigation scenario			2075 Zero irrigation scenario		
	Total land area (Mha)	Arable land and permanent crops (Mha)	Percent of arable land and permanent crops irrigated	Water withdrawal ($m^3 cap^{-1} yr^{-1}$)	Water availability ($m^3 cap^{-1} yr^{-1}$)	Use-to-resource ratio (percent)	Water withdrawal ($m^3 cap^{-1} yr^{-1}$)	Water availability ($m^3 cap^{-1} yr^{-1}$)	Use-to-resource ratio (percent)	Water withdrawal ($m^3 cap^{-1} yr^{-1}$)	Water availability ($m^3 cap^{-1} yr^{-1}$)	Use-to-resource ratio (percent)
Ivory coast	32	7	1	53	9068	1	282	2495	11	98	2311	4
Cameroon	48	7	0.5	32	18901	0	279	6839	4	95	6655	1
Uganda*	24	7	0.1	18	829	2	235	520	45	51	336	15
Zambia	75	5	1	206	12502	2	608	4767	13	424	4583	9
Middle East & North Africa												
Iran	163	19	39	697	110	634	305	36	848	300	31	976
Sudan*	251	17	12	635	801	79	675	415	163	670	410	164
Morocco	45	10	13	400	207	193	675	43	1570	670	38	1775
Algeria	238	8	7	170	63	270	303	19	1596	298	14	2168
Latin America and the Caribbean												
Brazil	855	65	4	246	38985	1	1090	23114	5	653	22677	3
Mexico	196	27	24	863	2183	40	1433	1511	95	996	1074	93
Argentina	278	27	6	843	6253	13	2496	5356	47	2059	4919	42
Western Europe												
Turkey	77	28	15	569	2030	28	1318	482	274	911	75	1220
France	55	19	9	593	3357	18	1610	3002	54	1203	2595	46
Spain	51	19	19	843	2642	32	1100	2013	55	693	1606	43
Germany	36	12	4	561	1474	38	1648	1467	112	1241	1060	117
Italy	30	11	25	929	2289	41	1277	2236	57	870	1829	48
UK	24	6	2	243	2240	11	1204	2366	51	797	1959	41
Central and Easterns Europe												
Poland	32	14	1	352	1061	33	2400	834	288	1699	133	1281
Romania*	24	10	31	1467	1158	127	5389	903	597	4688	202	2325

Note: Countries marked with an asterisk (*) in the tables have significant river inflow from other countries (>50 percent of internal renewable resources). This inflow is not taken into account in the water availability modeling in Alcamo et al. (1997).
The basic land and irrigation data was downloaded from the on-line FAOSTAT data base (http://apps.fao.org/) in December 2000.

requirements. FAO Irrigation and Drainage Paper 56. Food and Agriculture Organization of the United Nations, Rome, Italy.
Arnell, N.W., 1999. Climate change and global water resources. Global Environmental Change 9, S31–S49.
Arnell, N., Liu, C., 2001. Hydrology and water resources. In: McCarthy, J.J., Canziani, O.F., Leary, N.A., Dokken, D.J., White, K.S. (Eds.), Climate Change 2001: Impacts, Adaption, and Vulnerability. Cambridge University Press, Cambridge, pp. 191–233.
Arnell, N., Bates, B., Lang, H., Magnuson, J.J., Mulholland, P., 1995. Hydrology and freshwater ecology. In: Watson, R.T., Zinyowera, M.C., Moss, R.H., Dokken, D.H. (Eds.), Climate Change 1995. Impacts, Adaption and Mitigation of Climate Change: Scientific-Technical Analyses. Cambridge University Press, Cambridge, pp. 325–363.
Aronsson, P., Perttu, K., 2001. Willow vegetation filters for wastewater treatment and soil remediation combined with biomass production. Forestry Chronicle 77 (2), 293–299.
Bain, R.L., Overend, R.P., Craig, K.R., 1998. Biomass-fired power generation. Fuel Processing Technology 54, 1–16.
Beale, C.V., Morison, J.I.L., Long, S.P., 1999. Water use efficiency of C_4 perennial grasses in a temperate climate. Agricultural and Forest Meteorology 96, 103–115.
Beiwinga, E.E., van der Bijl, G., 1996. Sustainability of energy crops in Europe: A methodology developed and applied. Centre for Agriculture and Environment, Utrecht.
Berndes, G., Börjesson, P., 2001. Implications of irrigation and water management for the net energy performance of bioenergy systems. Department of Physical Resource Theory, Chalmers University of Technology and Göteborg University, Sweden.
Berndes, G., Hoogwijk, M., van den Broek, R., 2002. The contribution of biomass in the future global energy supply: a review of 17 studies. To appear in Biomass and Bioenergy.
Black, C., Ong, C., 2000. Utilisation of light and water in tropical agriculture. Agricultural and Forest Meteorology 104, 25–47.
Bouwer, H., 2000. Integrated water management: emerging issues and challenges. Agricultural Water Management 45, 217–228.
Börjesson, P., 1999a. Environmental effects of energy crop cultivation in Sweden: economic valuation. Biomass and Bioenergy 16, 155–170.
Börjesson, P., 1999b. Environmental effects of energy crop cultivation in Sweden: identification and quantification. Biomass and Bioenergy 16, 137–154.
BP Amoco, 1999. The 1999 Statistical Review of World Energy (www.bpamoco.com).
Carpentieri, A.E., Larson, E.D., Woods, J., 1993. Future biomass-based electricity supply in northeast Brazil. Biomass and Bioenergy 4 (3), 149–173.
Cartwright, P.S., 1992. Industrial wastewater treatment with membranes—a United States perspective. Water Science and Technology 25 (10), 373–390.
Consonni, S., Larson, E.D., 1996. Biomass-gasifier/aeroderivative gas turbine combined cycles: part B–performance calculations and economic assessment. Journal of Engineering for Gas Turbines and Power 118, 516–525.
Cook, J., Beyea, J., 2000. Bioenergy in the United States: progress and possibilities. Biomass and Bioenergy 18, 441–455.
Cooke, D.A., Scott, R.K. (Eds.), 1993. The sugar beet crop: Science into practice. World Crop Series, Chapman & Hall, 2–6 Boundary Row, London, SE1 8HN, UK.
Dushenkov, S., Mikheev, A., Prokhnevsky, A., Ruchko, M., Sorochinsky, B., 1999. Phytoremediation of radioceasium-contaminated soil in the vicinity of Chernobyl. Ukraine. Environmental Science and Technology 33, 469–475.
Ebert, F., Büttner, H., 1996. Recent investigations with nozzle scrubbers. Powder Technology 86, 31–36.
Ercoli, L., Mariotti, M., Masoni, A., Bonari, E., 1999. Effect of irrigation and nitrogen fertilization on biomass yield and efficiency of energy use in crop production of Miscanthus. Field Crops Research 63, 3–11.
European Commission, 1997. Energy for the future: renewable sources of energy. White paper for a community strategy and action plan.
Evans, J., 1992. Plantation Forestry in the Tropics. Clarendon Press/Oxford University Press, Oxford.
Falkenmark, M., 1989. The massive water scarcity now threatening Africa: why isn't it being addressed? Ambio 18 (2), 112–118.
Falkenmark, M., 1997. Meeting water requirements of an expanding world population. In: Greenland, D.J., Gregory, P.J., Nye, P.H. (Eds.), Land Resources: On The edge of the Mathusian Precipice? Philosophical Transactions: Biological Sciences, Vol. 352. The Royal Society of London, pp. 929–936.
FAO, 2000. FAOSTAT Online Database. Food and Agriculture Organisation of the United Nations, Rome, Italy.
Frings, R.M., Hunter, I.R., Mackie, K.L., 1992. Environmental requirements in thermochemical and biochemical conversion of biomass. Biomass and Bioenergy 2, 263–278.
George, R.J., Nulsen, R.A., Ferdowsian, R., Raper, G.P., 1999. Interactions between trees and groundwaters in recharge and discharge areas—a survey of western Australian sites. Agricultural Water Management 39, 91–113.
Giampietro, M., Ulgiati, S., Pimentel, D., 1997. Feasibility of large-scale biofuel production. Bioscience 47 (9), 587–600.
Gleick, P.H. (Ed.), 1993. Water in Crisis: A Guide to the World's Fresh Water Resources. Oxford University Press, New York.
Gleick, P.H., 1994. Water and energy. In: Socolow, R. H., Anderson, D., Harte, J. (Eds.), Annual Review of Energy and the Environment, Vol. 19. Annual Reviews Inc., Paulo Alto, CA, USA, pp. 267–299.
Grigal, D.F., Berguson, W.E., 1998. Soil carbon changes associated with short-rotation systems. Biomass and Bioenergy 14, 371–378.
Gustavsson, L., Börjesson, P., 1998. CO_2 mitigation cost. Bioenergy systems and natural gas systems with decarbonization. Energy Policy 26 (9), 699–713.
Hall, D.O., Rosillo-Calle, F., Williams, R.H., Woods, J., 1993a. Biomass for energy: supply prospects. In: Johansson, T.B., Kelly, H., Reddy, A.K.N., Williams, R.H. (Eds.), Renewable Energy: Sources for Fuels and Electricity. Island Press, Washington, DC, pp. 593–651.
Hall, D.O., Woods, J., Scurlock, J.M.O., 1993b. Biomass production and data. In: Hall, D.O., Scurlock, J.M.O., Bolhar-Nordenkampf, H.R., Leegood, R.C., Long, S.P. (Eds.), Photosynthesis and Production in a Changing Environment: a Field and Laboratory Manual. Chapman & Hall, London, pp. 425–444.
Hasselgren, K., 1998. Use of municipal waste products in energy forestry: highlights from 15 years of experience. Biomass and Bioenergy 15, 71–74.
Henderick, P., Williams, R.H., 2000. Trigeneration in a northern Chinese village using crop residues. Energy for Sustainable Development 4 (3), 26–42.
Heuperman, A., 1999. Hydraulic gradient reversal by trees in shallow water table areas and repercussions for the sustainability of tree-growing systems. Agricultural Water Management 39, 153–167.
Houghton, J.T., Callander, B.A., Varney, S.K. (Eds.), 1992. Climate Change 1992. The Supplementary Report to the IPCC Scientific Assessment. Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom.
Houghton, J.T., Filho, L.G.M., Bruce, J., Lee, H., Callander, B.A., Haites, E., Harris, N., Maskell, K. (Eds.), 1995. Climate change 1994—Radiative Forcing of Climate Change and an Evaluation of the IPCC IS92 Emission Scenarios. Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom.

Hughes, W.E.M., 1998. Biomass integrated-gasification/gas turbine power generation in Zimbabwe. Ph.D. Department of Mechanical and Aerospace Engineering.

IEA, 1994. Biofuels. Organisation for Economic Co-Operation and Development (OECD) and International Energy Agency (IEA).

IEA, 1998. Energy statistics & balances. International Energy Agency/ Organisation for Economic Co-operation and Development, Paris.

IPCC, 2000. Special Report on Emission Scenarios. Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge.

Johansson, T.B., Kelly, H., Reddy, A.K.N., Williams, R.H., 1993. Renewable Energy: Sources for Fuels and Electricity. Island Press, Washington, DC.

Kaczmarek, Z., 1995. Water resources management. In: Watson, R.T., Zinyowera, M.C., Moss, R.H., Dokken, D.H. (Eds.), Climate Change 1995. Impacts, Adaption and Mitigation of Climate Change: Scientific-Technical Analyses. Cambridge University Press, Cambridge, pp. 469–486.

Kartha, S., Larson, E.D., 2000. A Bioenergy Primer: Modernized Biomass Energy for Sustainable Development. United Nations Development Programme, New York.

Katofsky, R.E., 1993. The production of fluid fuels from biomass. MSE Thesis.

Kaylen, M., Van Dyne, D.L., Choi, Y.-S., Blase, M., 2000. Economic feasibility of producing ethanol from lignocellulosic feedstocks. Bioresource Technology 72, 19–32.

Kho, R.M., 2000. A general tree-environment-crop interaction equation for predictive understanding of agroforestry systems. Agriculture, Ecosystems and Environment 80, 87–100.

Kinzig, A., Schneider, L., Solorzano, L., Larson, E.D., 1999. GIS-assisted calculation of potential biomass yields applied to a regional assessment of land availability for biomass energy in Northeast Brazil. Center for Energy and Environmental Studies, Princeton University, Princeton, NJ.

Kort, J., Collins, M., Ditsch, D., 1998. A review of soil erosion potentials associated with biomass crops. Biomass and Bioenergy 14, 351–360.

Larson, E., Kartha, S., 2000. Expanding roles for modernized biomass energy. Energy for Sustainable Development 4 (3), 15–25.

Lazarus, M., Greber, L., Hall, J., Bartels, C., Bernow, S., Hansen, E., Raskin, P., von Hippel, D., 1993. Towards a Fossil Free Energy Future. Stockholm Environmental Institute–Boston Center, Boston.

Ledin, S., 1998. Environmental consequences when growing short-rotation forests in Sweden. Biomass and Bioenergy 15, 49–56.

Loomis, R.S., Connor, D.J., 1992. Crop Ecology: Productivity and Management in Agricultural Systems. Cambridge University Press, Cambridge.

Lynd, L.R., 1996. Overview and evaluation of fuel ethanol from cellulosic biomass: technology, economics, the environment, and policy. Annual Review of Energy and the Environment 21, 403–465.

Lysen, E.H., Ouwens, C.D., van Onna, M.J.K., Blik, K., Okken, P.A., Goudriaan, J., 1992. The feasibility of biomass production for the Netherlands energy economy. Netherlands Agency for Energy and the Environment (NOVEM), The Netherlands.

Macedo, I.D.C., 1998. Greenhouse gas emissions and energy balances in bio-ethanol production and utilization in Brazil (1996). Biomass and Bioenergy 14 (1), 77–81.

Madakadze, I.C., Stewart, K., Peterson, P.R., Coulman, B.E., Samson, R., 1998. Light interception, use-efficiency and energy yield of switchgrass (*Panicum Virgatum L.*) grown in a short season area. Biomass and Bioenergy 15 (6), 475–482.

Mann, M.K., 1995. Technical and economic assessment of producing hydrogen by reforming syngas from the Battelle indirectly heated biomass gasifier. National Renewable Energy Laboratory, Golden, CO, USA.

McLaughlin, S.B., Walsh, M.E., 1998. Evaluating environmental consequences of producing herbaceous crops for bioenergy. Biomass and Bioenergy 14, 317–324.

Moomaw, W.R., Moreira, J.R., 2001. Technological and economic potential of greenhouse gas emissions reduction. In: Metz, B., Davidson, O., Swart, R., Pan, J. (Eds.), Climate Change 2001: Mitigation, Contribution of Working Group III to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp. 167–277.

Muchow, R.C., Robertson, M.J., Wood, A.W., 1996a. Growth of sugarcane under high input conditions in tropical Australia. II. Sucrose accumulation and commercial yield. Field Crops Research 48, 27–36.

Muchow, R.C., Robertson, M.J., Wood, A.W., Keating, B.A., 1996b. Effect of nitrogen on the time-course of sucrose accumulation in sugarcane. Field Crops Research 47, 143–153.

Nakicenovic, N., Grübler, A., McDonald, A., 1998. Global Energy Perspectives. International Institute for Applied Systems Analysis/ World Energy Council, Cambridge University Press, Cambridge.

Nonhebel, S., 1995. Harvesting the sun's energy using agro-ecosystems. Department of Theoretical Production Ecology, Wageningen Agricultural University, Wageningen.

Ogden, J.M., Williams, R.H., Fulmer, M.E., 1990. Cogeneration applications of biomass gasifier/gas turbine technologies in the cane sugar and alcohol industries. In: Tester, J.W., Wood, D.O., Ferrari, N.A. (Eds.), Energy and Environment in the 21st Century. Massachusetts Institute of Technology, Cambridge, MA, USA, March 26–28.

Ong, C.K., Odongo, J.C.W., Marchall, F., Black, C.R., 1992. Water use in agroforestry systems in semi-arid India. In: Calder, I.R., Hall, R.L., Adlard, P.G. (Eds.), Growth and Water Use of Plantations. Wiley, Chichester, pp. 347–358.

Ong, C.K., Black, C.R., Wallace, J.S., Khan, A.A.H., Lott, J.E., Jackson, N.A., Howard, S.B., Smith, D.M., 2000. Productivity, microclimate and water use in Grevillea robusta-based agroforestry systems on hillslopes in semi-arid Kenya. Agriculture, Ecosystems and Environment 80, 121–141.

Parameswaran, M., 1999. Urban wastewater use in plant biomass production. Resources, Conservation and Recycling 27, 39–56.

Perttu, K.L., 1998. Environmental justification for short-rotation forestry in Sweden. Biomass and Bioenergy 15, 1–6.

Perttu, K.L., Kowalik, P.J., 1997. Salix vegetation filters for purification of waters and soils. Biomass and Bioenergy 12, 9–19.

Peterson, C.L., Hustrulid, T., 1998. Carbon cycle for rapeseed oil biodiesel fuels. Biomass and Bioenergy 14 (2), 91–101.

Postel, S., 1992. Last Oasis: Facing Water Scarcity. W.W. Norton & Company, New York.

Postel, S., 1998. Water for food production: will there be enough in 2025? Bioscience 48, 629–637.

Postel, S.L., Daily, G.C., Ehrlich, P.R., 1996. Human appropriation of renewable fresh water. Science 271, 785–788.

Ranney, J.W., Mann, L.K., 1994. Environmental considerations in energy crop production. In: Wright, L.L., Hohenstein, W.G. (Eds.), Dedicated Feedstock Supply Systems: Their Current Status in the USA. Special Issue, Biomass and Bioenergy, Vol. 6, no. 3, Elsevier Science Ltd, Amsterdam, pp. 211–228.

Raskin, P., Hansen, E., Margolis, R., 1995. Water and Sustainability: a Global Outlook. Stockholm Environment Institute, Boston.

Ravindranath, N.H., Hall, D.O., 1995. Biomass, Energy, and Environment: a Developing Country Perspective from India. Oxford University Press, Oxford, UK.

Reddy, A.K.N., Williams, R.H., Johansson, T.B., 1997. Energy after Rio; Prospects and Challenges. United Nations Development Programme, New York, NY, USA.

Rockström, J., Gordon, L., Folke, C., Falkenmark, M., Engwall, M., 1999. Linkages among water vapor flows, food production, and terrestrial ecosystem services. Conservation Ecology 3 (2), 5.

Seckler, D., Amarasinghe, U., Molden, D., de Silva, R., Barker, R., 1998. World Water Demand and Supply, 1990–2025: Scenarios and Issues. International Water Management Institute, Colombo, Sri Lanka.

Shapouri, H., Duffield, J.A., Graboski, M.S., 1995. Estimating the net energy balance of corn ethanol. Economic Research Service, United States Department of Agriculture, Washington, DC, p. 15.

Shiklomanov, I.A. (Ed.), 1997. Comprehensive Assessment of the Freshwater Resources of the World: Assessment of Water Resources and Water Availability in the World, World Meteorological Organization.

Sims, R., Riddell-Black, D., 1998. Sustainable production of short rotation forest biomass crop using aqueous waste management systems. Biomass and Bioenergy 15, 75–82.

Solley, W.B., Pierce, R.R., Perlman, H.A., 1998. Estimated use of water in the United States in 1995. US Department of the Interior/US Geological Survey.

Sudha, P., Ravindranath, N.H., 1999. Land availability and biomass production potential in India. Biomass and Bioenergy 16 (3), 207–221.

The White House, 1999a. Executive Memorandum accompanying the Executive Order 13134: Developing and Promoting Biobased Products and Bioenergy. Office of the Press Secretary, August 12, 1999.

The White House, 1999b. Executive Order 13134: Developing and Promoting Biobased Products and Bioenergy. Office of the Press Secretary, August 12, 1999.

Tolbert, V., 1998. Guest editorial. Biomass and Bioenergy 14, 301–306.

Turkenburg, W.C., 2000. Renewable energy technologies. In: Goldemberg, J. (Ed.), World Energy Assessment, UNDP/UN-DESA/WEC.

Tuskan, G.A., 1998. Short-rotation woody crop supply systems in the United States: what do we know and what do we need to know? Biomass and Bioenergy 14, 317–324.

UNDP/WEC, 2001. World energy assessment: energy and the challenges of sustainability. United Nations development programme, United Nations Department of Economic and Social Affairs, World Energy Council, New York, USA.

USDOE/EPRI, 1997. Renewable energy technology characterizations. Office of Utility Technologies, Energy Efficiency and Renewable Energy, US Department of Energy, Electric Power Research Institute.

von Sivers, M., Zacchi, G., 1993. A techno-economical comparison of three processes for the production of ethanol from wood. Department of Chemical Engineering, Lund Institute of Technology, Lund, Sweden.

Vörösmarty, C.J., Green, P., Salisbury, J., Lammers, R.B., 2000. Global water resources: vulnerability from climate change and population growth. Science 289, 284–288.

Wichelns, D., 2001. The role of "virtual water" in efforts to achieve food security and other national goals, with an example from Egypt. Agricultural Water Management 49, 131–151.

Wilkie, A.C., Riedesel, K.J., Owens, J.M., 2000. Stillage characterization and anaerobic treatment of ethanol stillage from conventional and cellulosic feedstocks. Biomass and Bioenergy 19, 63–102.

Williams, R., 1994. Role for biomass energy in sustainable development. In: Socolow, R., Andrews, C., Berkhout, F., Thomas, V. (Eds.), Industrial Ecology and Global Change. Cambridge University Press, Cambridge, UK, pp. 199–225.

Williams, R.H., 1995. Variants of a low CO_2-emitting energy supply system (LESS) for the world: Prepared for the IPCC Second Assessment Report Working Group IIa, Energy Supply Mitigation Options. Pacific Northwest Laboratories.

Williams, R.H., Larson, E.D., 1993. Advanced gasification-based biomass power generation. In: Johansson, T.B., Kelly, H., Reddy, A.K.N., Williams, R.H. (Eds.), Renewable Energy: Sources for Fuels and Electricity. Island Press, Washington, DC, pp. 729–785.

Williams, R.H., Larson, E.D., 1996. Biomass gasifier gas turbine power generating technology. Biomass and Bioenergy 10 (2–3), 149–166.

Williams, R.H., Larson, E.D., Katofsky, R.E., Chen, J., 1995. Methanol and hydrogen from biomass for transportation. Energy for Sustainable Development 1 (5), 18–34.

Wirsenius, S., 2000. Human use of land and organic materials: modeling the turnover of biomass in the global food system. Ph.D. Department of Physical Resource Theory.

Wyman, C.E., Bain, R.L., Hinman, N.D., Stevens, D.J., 1993. Ethanol and methanol from cellulosic biomass. In: Johansson, T.B., Kelly, H., Reddy, A.K.N., Williams, R.H. (Eds.), Renewable Energy: Sources for Fuels and Electricity. Island Press, Washington, DC, pp. 865–923.