WBGU
Wissenschaftlicher Beirat der Bundesregierung
Globale Umweltveränderungen

materialien

Göran Berndes:

Water demand for global bioenergy production: trends, risks and opportunities

Externe Expertise für das WBGU-Hauptgutachten
"Welt im Wandel: Zukunftsfähige Bioenergie und nachhaltige Landnutzung"

Berlin 2008

Externe Expertise für das WBGU-Hauptgutachten
"Welt im Wandel: Zukunftsfähige Bioenergie und nachhaltige Landnutzung"
Berlin: WBGU
ISBN 978-3-9396191-21-9
Verfügbar als Volltext im Internet unter http://www.wbgu.de/wbgu_jg2008.html

Autor: Göran Berndes
Titel: Water demand for global bioenergy production: trends, risks and opportunities
Göteborg, Berlin 2008
Veröffentlicht als Volltext im Internet unter http://www.wbgu.de/wbgu_jg2008_ex02.pdf

Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen
Geschäftsstelle
Reichpietschufer 60–62, 8. OG.
10785 Berlin

Telefon	(030) 263948 0
Fax	(030) 263948 50
E-Mail	wbgu@wbgu.de
Internet	http://www.wbgu.de

Alle WBGU-Gutachten können von der Internetwebsite http://www.wbgu.de in deutscher und englischer Sprache herunter geladen werden.

Water demand for global bioenergy production: trends, risks and opportunities

Göran Berndes
Department of Energy and Environment, Physical Resource Theory
Chalmers University of Technology, SE-412 96 Göteborg, Sweden

Contact: Tel.: +46 730 79 42 87; E-mail: goran.berndes@chalmers.se

1 Preface

In its 2008 flagship report, the WBGU addresses the question of sustainable land-use and bioenergy use under changing climate conditions. Taking an analysis of global land-use under current and future climate impacts as a starting point, the report aims at finding out what opportunities and risks the global use of bioenergy entails. The goal of the report is to provide information and recommendations for decision-makers on the global sustainable potentials and risks in bioenergy use. The challenge will be to quantify the global niche that a sustainable use of bioenergy could occupy while meeting competing demands in terms of food security, conservation of biodiversity, and infrastructure development.

This report intends to provide a readable global overview on the nexus between water availability and increasing bioenergy production and possible consequences for global bioenergy potentials. One basis for the analyses underlying the report is a number of lead questions provided by WBGU. The primary focus is the water situation in agriculture (i.e., the global food system). However, bioenergy systems based on forest biomass is included in order to account for the total biomass resource base. Furthermore, some of the assessed biomass supply systems qualify as forests and expansion of these therefore takes the form of afforestation/reforestation activities.

The short report format makes it necessary to make the report concise and "straight to the point", only summarizing background information and context. The reference list is intended to support further studies of the subject treated, in addition to supporting statements made. The report also includes suggestions on research that would advance the scientific knowledge in this field.

2 Table of contents

3 Introduction

Freshwater is already scarce in some regions of the world. A growing population and changing dietary trends mean a steeply rising water demand. Under the impact of climate change the population at risk of water stress could increase substantially by the end of the century. In this context, water demand for bioenergy production might place an additional burden on water availability worldwide and induce increased competition over water resources in an increasing number of regions. However, bioenergy demand also leads to new opportunities to develop strategies to *adapt* to climate change in agriculture: a number of crops that are suitable for bioenergy production are drought tolerant and relatively water efficient and by adopting such crops farmers may better cope with a change in precipitation patterns and increased rates of evapotranspiration[1] (ET) due to higher temperature.

The possibility to integrate the cultivation of new types of bioenergy crops within expanded agricultural systems in a modified water resource context presents challenges as well as opportunities in the development of water and land use strategies. This report aims at providing a global overview on the challenges outlined above and to discuss the possible role of bioenergy in a water scarce world. The view on water will include the entire global water resource, i.e. the runoff in rivers, lakes and groundwater aquifers – the blue water flow – and the water flow that supports and is consumed by biomass production – the green water flow, i.e. the water in the root zone of the soil (stemming from precipitation) that controls plant growth.

3.1 Bioenergy may become a human use of photosynthesis that is comparable in scale to that for agriculture or forestry

Before discussing possible effects of bioenergy growth on increasing human water use[2] – including the possibilities of better land and (green/blue) water resource management to intensify biomass production for food and bioenergy – illustrative quantifications will be presented in order to relate the prospective bioenergy demand to the present major biomass uses in the world.

As can be seen in Figure 1, the quantitative production of fossil resources is much larger than the biomass production in agriculture and forestry. Petroleum is to some extent used for the production of plastics and bulk chemicals, some 10-15 percent of the coal is used in steel

---

[1] Water is lost to the atmosphere in the process of crop transpiration. Water vapour diffuses from the inside of 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 ET losses.

[2] Water use will in this report refer to the ET that brings water from the possibly plant-available to not available, being water vapour in the atmosphere. Deep percolation may make water unavailable deep in the ground, but focus is here placed on ET.

production, and fossil gas (and to some extent also other fossil resources) are used for the production of synthetic fertilizers. But it is the use of fossil fuels in the energy sector that is the dominating source behind society's exploitation of fossil resources: the decoupling of societal energy use from biological productivity, that took place more than 100 years ago, has now brought us to energy consumption levels that make it difficult to return to a situation where the global society solely relies on biomass for energy. At the same time, global energy consumption is expected to more than double during the 21st century. This means that the requirements of CO_2 neutral energy may have to grow to levels much larger than the present global total fossil fuel use, if we are to reach ambitious stabilization targets[3]. ***A dramatic increase in the output from agriculture and forestry is required for making biomass an important primary energy source on the global level.***

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). "Pasture & forage" refers to the part eaten by grazing animals. "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. Based on Berndes (2006).

The conclusion on global level above holds also for most countries. Biomass is presently an important source of energy in developing countries, but this is at a very low level of per

[3] Hoffert et al. (1998, 2002) provide readable accounts of the energy implications of future atmospheric CO_2 stabilization levels. Pacala and Socolow (2004) provide some moderation of the technology challenge indicated by Hoffert et al, which is re-emphasized by Pielke et al (2008) arguing that the reference scenarios used by the IPCC's fourth assessment report (AR4) – SRES – seriously underestimates the technological challenge associated with stabilizing greenhouse-gas concentrations.

capita energy use and the biomass use – mainly combustion of wood and agricultural residues – has severe negative impacts. The combustion in confined spaces leads to indoor air pollution to which women and children are primarily exposed. This exposure has severe health consequences, including respiratory illnesses and premature death (WHO 2002). Furthermore, in many instances the biomass use puts large pressure on local natural resources, leading to overexploitation with vegetation and soil degradation. The clear link between access to energy services and poverty alleviation and development is a strong motive to substantially improve and increase the supply of energy services in developing countries (Takada and Porcaro 2005, UNDP 2005).

A few countries with large forest industries are unique in that the residues and by-flows in the forest industry can make up a considerable proportion of the energy supply. This is clearly indicated in Figure 2, in which the industrial wood production gives an indication of the size of the biomass flows in the forest sector in different countries which might be available for energy purposes (the waste product flows are of the same magnitude as the biomass flow in the form of products). Global industrial wood production provides slightly below 16 EJ/year, or about 2.5 GJ/capita/year, which can be compared to the 390 EJ (60 GJ/capita) of fossil fuels that were commercially traded globally in 2005 (BP 2007).

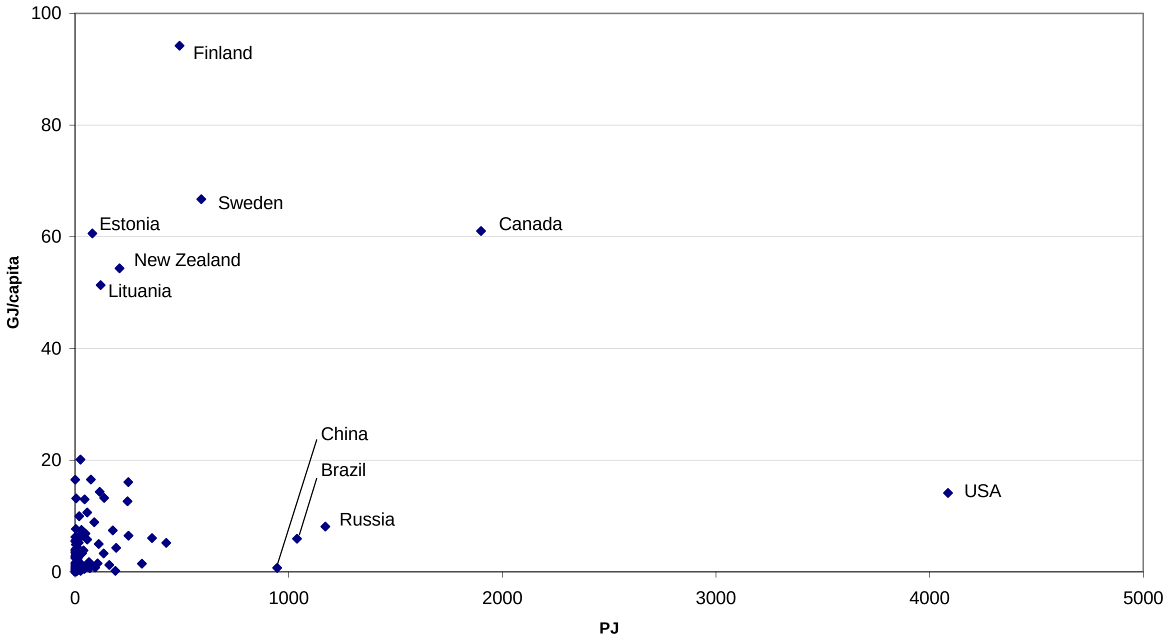

Figure 2. Industrial roundwood production in the countries of the world: average for 2000–2003, converted to energy in the form of biomass based on an assumed energy content of 10 GJ/m3 of wood. The figure shows the dominant industrial wood producers in the world and the production per capita in different countries. Based on data provided by the UN Food and Agriculture Organization, FAO (FAOSTAT 2008).

If we take a closer look at the EU and also compare with current energy use, it is clear that the preconditions vary considerably from one Member State to the next (Figure 3). Sweden and Finland have the largest forest extraction in EU[4] and, as can be seen in Figure 3, the extraction is also substantial relative to the domestic energy use. The three Baltic States and a few other MS also have a fairly large forest extraction relative to their own energy use and their extraction relative to forest growth is also less than in Sweden and Finland: countries close to the dotted diagonal have a net annual increment that is approximately twice as large as the extraction. For the entire EU, forest extraction is equal to about half the net annual increment and is, as can be seen from the figure, rather modest compared to the gross energy consumption (about 5 %).

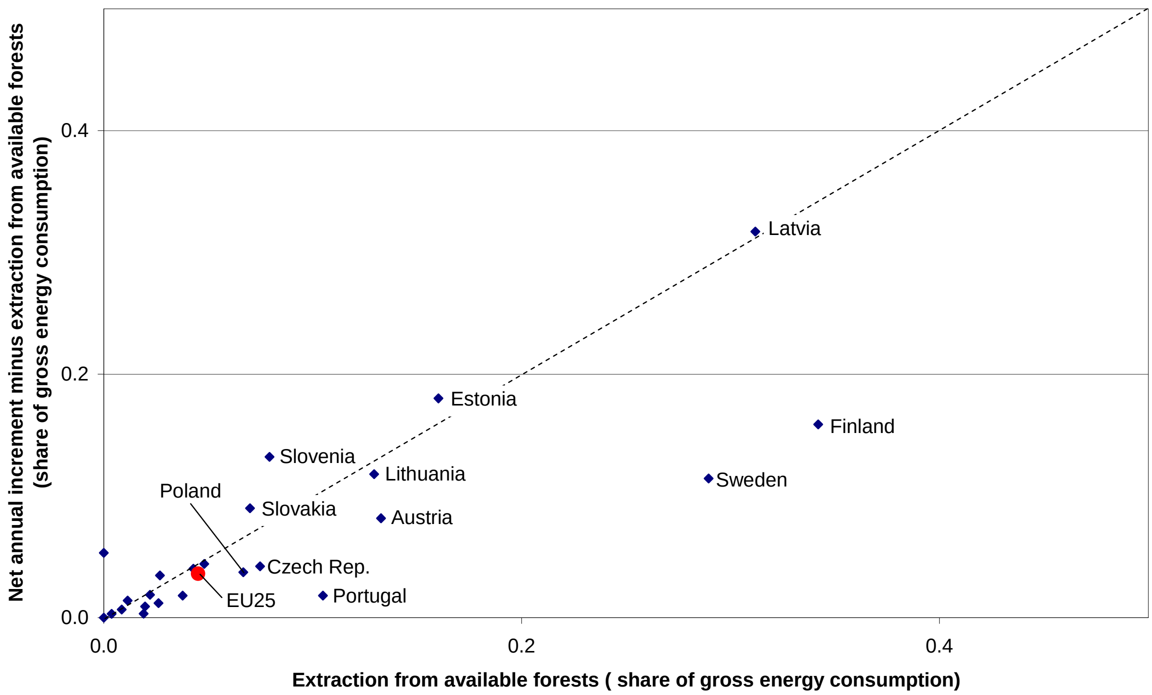

Figure 3. Comparison between gross energy consumption and forest extraction, and the balance between net annual increment and forest extraction in EU Member States. The forest extraction and balance are converted to bioenergy based on assumed energy content of 10 GJ/m3 of wood and then divided by each country's gross energy consumption. The net annual increment applies to parts of a country's forest that is judged available for forest extraction. Data sources: Eurostat statistical database and EC (2006).

Turning to agriculture, Figure 1 clearly showed that considerable biomass flows are generated in this sector. A substantial part (often more than half) of the biomass production above ground consists of residues. Far from all these residues can be used for energy purposes. Some must be left on the fields for soil conversation purposes and some are utilised for other purposes such as feeding and bedding in livestock production. On the other hand, waste

[4] Corresponding to about 600 and 500 PJ, respectively. Forest wood extraction is also large in France and Germany, but compared to the energy use in these countries it is only a few percent. Forest extraction in Poland is about half the level in Finland and in Austria it is roughly one-third the Finnish level.

products with a possible energy use are also generated when the crops are processed in the food industry and a substantial part of the harvested food products ends up as post consumption waste. Thus, Figure 4 – showing the production of major crop types in the countries of the world – also gives a rough picture of the amount of residues and waste products generated within agriculture. The global production of the major crop types included in Figure 4 corresponds to about 60 EJ (10 GJ/capita). Once again, the global commercial trade in fossil fuels at roughly 390 EJ (60 GJ/capita) provides a relevant comparison.

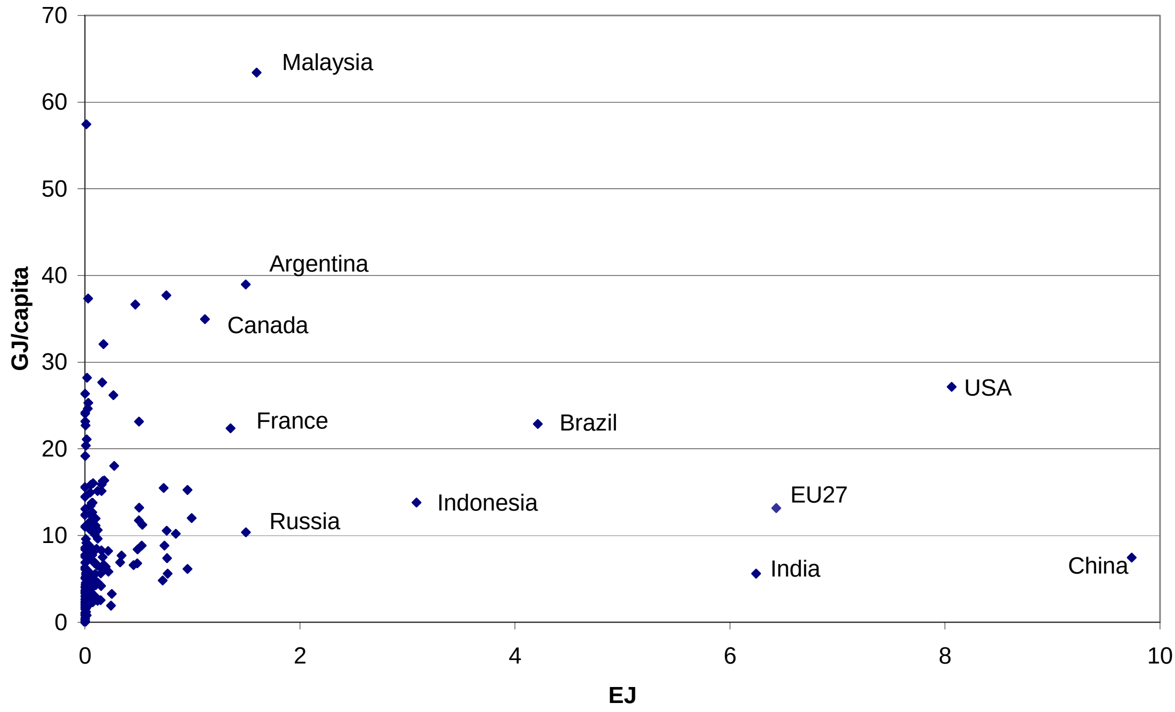

Figure 4. Production of major crop types (cereals, oilcrops, sugar crops, roots & tubers and pulses) in the countries of the world: average for 2002-2006, converted to energy units. The figure shows the dominant producers in the world and the production per capita in different countries. Based on data provided by the UN Food and Agriculture Organization, FAO (FAOSTAT 2008).

3.2 Efficiency increases along the food supply chain and the use of food system by-flows for energy could mitigate the water impacts of increasing demand for food and bioenergy

To the extent that bioenergy feedstocks consist of residues and biomass processing by-flows within the food (and forestry) sectors, water use for human purposes does not increase. The use of such flows improves the water productivity – more utility (e.g., both food and bioenergy) per unit water used – and also mitigates the demand on water for bioenergy, since bioenergy from residues can be produced without an increased pressure on water resources. The water that is used to produce the food and conventional forest products is the same water as will also produce the residues and by-flows potentially available for bioenergy.

The possibility to support an expanded cultivation of energy crops depends on the food sector development: the food supply chain efficiency and – not the least – the possible dietary changes linked to GDP growth in developing countries (see Figure 5). Several studies have stressed the resource-saving and environmental benefits of dietary changes in affluent societies, primarily in the form of substitution from animal to vegetable food (e.g.Carlsson-Kanyama (1998), Gerbens-Leenes & Nonhebel (2002), Smil (2002), Carlsson-Kanyama et al. (2003), Duchin (2005), de Boer et al. (2006), Elferink & Nonhebel (2007)). However, the analyses have mostly been based on hypothetical assumptions of consumption changes, rather than attempting to quantify the effects of (possibly) more plausible changes in diets, taking into account the fact that consumer preferences are generally quite conservative.

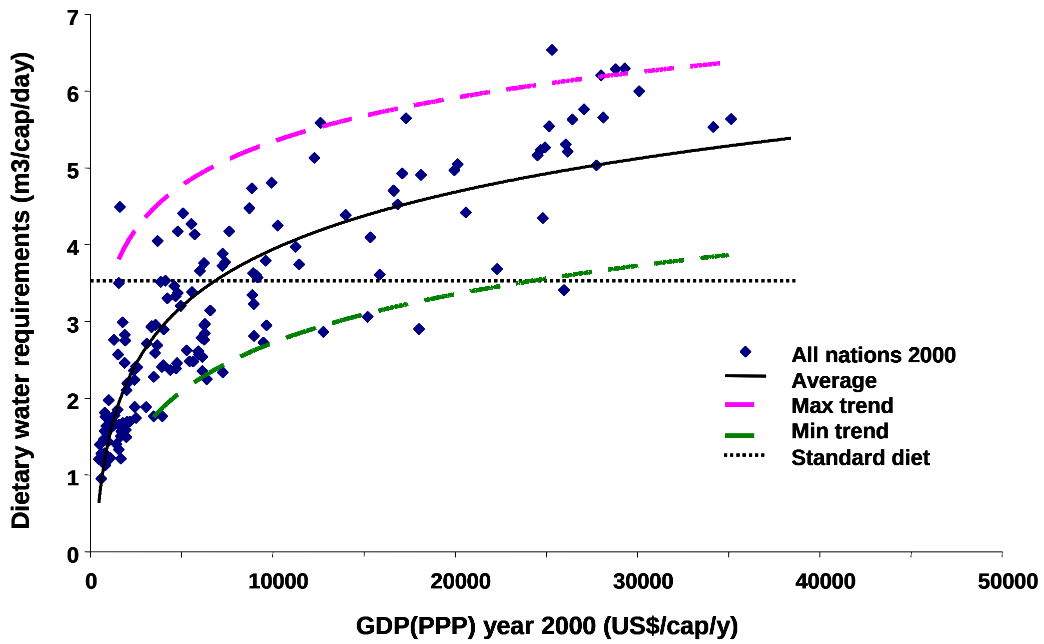

Figure 5. The graph shows water requirement for the food supply in countries at different levels of GDP (US$ per capita in year 2000). Regression lines for approximate 'maximum' and 'minimum' food supply in terms of water requirements are plotted (Lundqvist et al., 2007).

The total food system appropriation of biological productivity is many times larger than what is finally used by humans. Less than 10% of the global appropriation of terrestrial plant biomass production by the food system is estimated to end up in food commodities eaten (Wirsenius 2003a, 2003b). Animal food systems account for roughly two-thirds of the total appropriation of plant biomass, whereas their contribution to the human diet is less than 15% (gross energy basis). The ruminant meat systems have the greatest influence on the food system's biomass appropriation, because of the size of ruminant meat demand and the lower feed conversion efficiency of those systems. There is a large potential for improving the water productivity by raising efficiencies in animal food production. In most low and medium-income countries, feed-to-food conversion efficiencies can be increased substantially (Wirsenius et al. forthcoming) and increases in feed conversion efficiency will lead to increases in water productivity.

Using as starting point projections of global agriculture up to 2030 made by the Food and Agriculture Organization of the United Nations (Bruinsma, 2003), explorative scenarios were developed to investigate the influence of: (i) increased livestock productivity (IP), where the livestock productivity growth rates are higher than in the FAO study, but only slightly above the historical rates of the productivity increases since 1960; (ii) ruminant meat substitution (RS), where the IP scenario is modified by assuming a substitution of 20% of the beef, sheep and goat meat end-use with pig and poultry meat; and (iii) shifts to more vegetarian food and less food wastage (VE), where the RS scenario is further modified by assuming a somewhat increased efficiency in the end-use (i.e. less food wasted) and a shift in the structure of diets towards more vegetable and less animal food[5].

The results indicate that if the projections made by the FAO come true, the prospects for bioenergy will be less favourable. However, the alternative scenarios show that ***there is scope for a substantial mitigation of the long-term land and water use in the food sector by increases in efficiency along the food supply chain*.** Compared to the FAO scenario, the global harvested and grazed amount of biomass on croplands and pastures is reduced by 10, 17 and 20 percent in the IP, RS and VE scenarios, respectively. The reduced grazing requirement is especially substantial, being 23, 36 and 39 percent lower than in the FAO scenario in the three alternative scenarios and even substantially below the situation in the beginning of the scenario period, implying that large pastures could become available for other uses. If part of this land was targeted for bioenergy plantations, a considerable amount of biomass for energy could be produced without claiming land beyond what has already been appropriated. The water implications of such a land use shift are further discussed later in this report.

Figure 6 show that there are also potentially major bioenergy feedstocks to be found in the large pool of appropriated biomass not ending up as food: ***the utilization of harvest residues and biomass processing by-flows in the food and forestry sectors can clearly support a bioenergy industry of substantial scale and could mitigate the water demand related to a large scale bioenergy expansion.*** Furthermore, in all three alternative scenarios, the amount of crop residues available for energy purposes will be higher than in the reference scenario. This is mainly due to a lower use of crop residues as feed in those scenarios. The manure production is significantly lower in the IP, RS and VE scenarios, but the amount potentially available for energy remains rather constant due to a larger fraction of manure excretion occurring in animal confinements, instead of on pastures.

---

[5] This scenario applies only to selected regions: W Europe, N America & Oceania (total meat end-use: -25%); E Europe (-6%); and Latin America & Caribbean (-9%).

Without expanding the discussion of residue potentials further, it can also be concluded that besides developing attractive strategies for increasing the biomass supply for food and bioenergy, society should explore prospects for mitigating overall biomass demand growth by improving the efficiency in the entire food chain – including dietary changes towards less land/water-demanding food.

Plausible consumption changes include substitution between different types of meat, rather than total shifts from meat to vegetable food. The water saving potentials of substituting ruminant meat (cattle, lamb) with pig or poultry meat are likely to be substantial, since the land and biomass savings from such meat substitution are generally very large. Another option for obtaining less water-demanding food consumption patterns is to incorporate plant-derived products in ground meat and other types of processed products. With further development of the technology for producing plant protein isolates, combined with changes in food regulations to allow greater additions in food products, inclusion of plant-derived proteins in ground and processed meat could reach about 25-35% (Smil 2002).

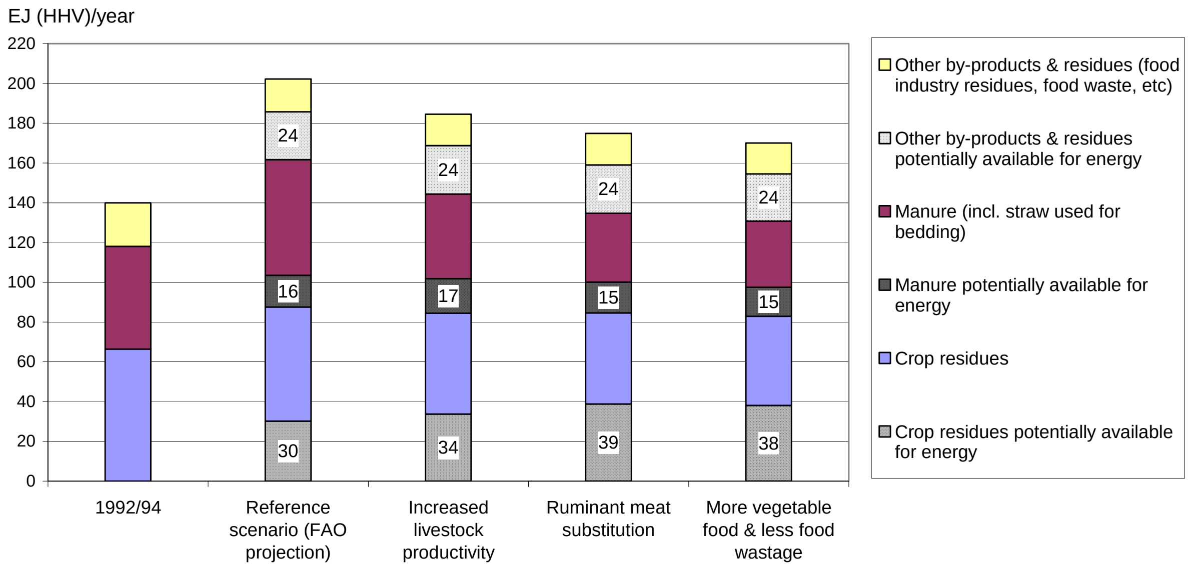

Figure 6: Estimated production of by-products and residues in the present global food system and in scenarios for 2030. The amounts possibly available for use as feedstock for bioenergy in the scenarios are indicated in the Figure (column fields with numbers). The Reference scenario depicts the FAO projection. Based on (Wirsenius et al. 2004).

Despite the above indication of substantial biomass resources in the form of residues and processing by-flows in the food and forestry sectors, ambitious climate and energy policies may lead to that dedicated cultivation of energy crops grows dramatically during the coming decades – simply because bioenergy demand may become even larger than what can be met based on food and forest sector by-flows, which are ultimately limited by the future (non-bioenergy) demand in these sectors and also subject to competitive uses (including for non-extractive uses such as soil conservation). As already noted, the requirements of CO_2 neutral energy may have to grow to levels above the present global total fossil fuel use, if we are to reach ambitious stabilization targets. Surveys of possible future energy sources come up with several candidates capable of supplying large amounts of CO_2 neutral energy, including solar and wind energy, bioenergy, nuclear fission and fusion, and fossil fuels with carbon capture and sequestration[6]. Yet, bioenergy is among the most cost competitive of the few technological options capable of tackling climate change already today, being a relatively low cost renewable option already competitive on some markets, and near penetration into new applications as policies, markets and related technologies develop.

Finally, when prospective advanced technologies eventually are in place, they will likely cost more than bioenergy, and therefore bioenergy will remain very competitive even under a scenario where advanced technologies have come to dominate the global energy supply: bioenergy might continue to increase until impacts of its expansion constrain a further growth. The next sections discuss the water implications of bioenergy expansion pathways where the cultivation of energy crops plays a prominent role. Initially, the specific water use of different bioenergy options is presented.

4 Water use of bioenergy systems based on cultivated feedstocks

4.1 The cultivation phase dominates the water use of bioenergy systems that are based on cultivated feedstocks

The water use related to the bioenergy systems consists of:

(i) ET connected to the energy crop production[7].
(ii) Evaporation of the water in the biomass feedstock connected to pre- and post harvest drying, feedstock pre-treatment and processing, and final bioenergy end use.
(iii) Evaporation of water that is withdrawn from water bodies for use in the post harvest biomass processing to produce electricity, biofuels and process heat.

Considering water use, as it has been defined above, ***it is the ET connected to the energy crop production that dominates the water use of bioenergy systems.***

---

[6] Besides the references given in an earlier footnote, the WGIII contribution to the IPCC AR4 (Sims, et al. (2007) "Mitigation of Climate Change") and the “World Energy Assessment” (Goldemberg 2000) – supplemented with the 2004 Update (Goldemberg and Johansson 2004) – provide readable overviews.

[7] Energy crop production, is here used as a broad term including the cultivation of herbaceous annuals (such as oil crops, cereals, hemp), perennial leys (such as switchgrass and elephant grass or Miscanthus) and woody crops, including (i) coppice systems utilizing tree crops such as willow, poplar and eucalypt species; and (ii) fast growing single stem plantations utilizing species such as hybrid poplar and eucalypt, grown in short rotations (6 to 12 years).

Comparing with the evaporation of water in the biomass feedstock: 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 . This is roughly a factor 50 or more below the estimated energy crop ET per GJ biofuel/electricity (presented later in the report).

Also the evaporation of water that is withdrawn for the feedstock conversion process is small compared to the ET from feedstock production. For electricity generation, most of the water that is withdrawn in power plants is used in the condenser to cool steam back into water[8]. 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[9] from which it can be recycled or returned to water bodies at a lowered temperature. Compared to the ET in energy crop production, electricity generation evaporates little water (Berndes 2002, DOE 2006). The same is true for the water evaporation connected to the conversion of biomass to biofuels, typically being two orders of magnitude lower than the energy crops ET or even less (Aden et al. 2002, Berndes 2002, Keeny and Muller 2006, Pate et al. 2007, Philips et al. 2007). The effluent production may be substantial for some bioenergy routes, potentially leading to local water quality challenges, but solutions are available for mitigating these environmental impacts.

Since it is the ET from energy crop production that dominates the water use, the remainder of this report will mainly focus on the cultivation phase of the bioenergy chain. The relative importance of energy crop production versus processing for total blue 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 of this report.

4.2 The supply of cultivated biomass can be increased without using more water

To the extent that feedstocks are produced based on cultivating energy crops, increasing bioenergy feedstock production can lead to increased water use for human purposes. However, recalling that water use here refers to the ET from the cropland; more biomass can be cultivated for food and bioenergy without using more water. The evaporation often dominates total ET for annual crops during the early part of the growing season, and may comprise 30-60 percent of seasonal ET, sometimes even up to around 80 percent. This is

---

[8] Besides for cooling, water is withdrawn to replace the water lost due to steam venting, and also for blowdown (cleaning) of boilers, washing of stacks and for employee and plant sanitation. However, most of the water used in thermoelectric plants is cooling water.

[9] The water withdrawals are reduced when recycling in cooling towers or ponds is employed, but a higher share of the cooling water is evaporated in such systems.

especially important in regions characterized by high evaporative demand, and under sparsely cropped farming systems (Figure 7).

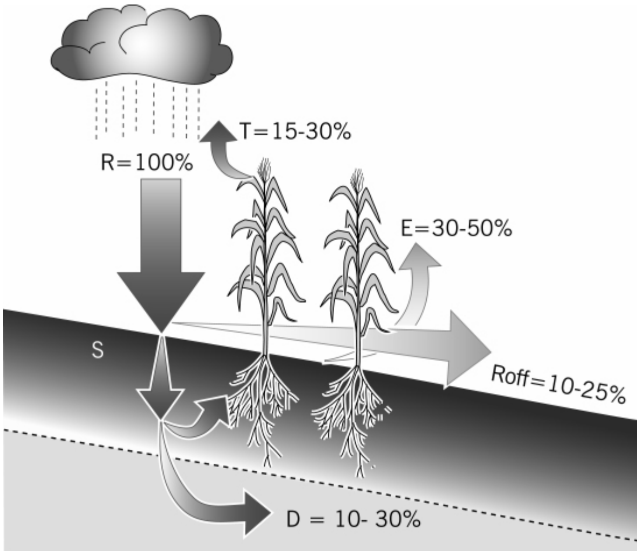

Figure 7. A general overview of typical rainfall partitioning in the semi-arid tropics in Sub-Saharan Africa (Rockström 1999). Unproductive losses of water (E) are large in relation to productive transpiration (T). Runoff (Roff) and drainage (D) are lost from the farmer's field, but can be used downstream.

A major task is to change the relationship between the non-beneficial evaporation and beneficial transpiration. A progressive decline of non-productive evaporation in favour of plant transpiration is possible through a combination of rainwater harvesting techniques and improved soil and land management. ***If a larger fraction of the rainfall can be harnessed and consumed in plant production, a boost in productivity and total production can be accomplished without necessarily increasing the pressure on freshwater in rivers, lakes and aquifers.***

On the other hand, increased allocation of freshwater flows to plant transpiration may lead to lowered groundwater levels, aggravate river depletion and reduce downstream water availability. The influence of increasing human water use for biomass production on different components of the hydrological cycle depends on:

- which types of bioenergy systems are established; energy crops differ in their water use and also in other aspects of relevance for the water context such as infiltration capacity,
- where in the world (and in the water basin) they are established; some regions with abundant water availability will not likely face water related difficulties while others may face an even more difficult water situation,
- which types of vegetation these systems replace; the net change in ET can be both negative and positive. Areas with sparse vegetation may experience increased ET when

bioenergy plantations are established, while reforestation of dense forests for the purpose of cultivating crops such as soybean and corn for biofuel leads to reduced ET[10].

This is discussed further in the Chapter on water resource management.

4.3 Water intensity of different bioenergy options that are based on cultivated feedstocks

The water intensity of different bioenergy options – here defined as water use per unit electricity or biofuel produced – varies substantially, and there is also a large variation in water intensity for the same biofuel option (Table 1). There are several reasons for this.

First, water use efficiency varies among crop types. A distinction can be made between C3 crops (about 95% of Earth's plant biomass) and C4 crops, which generally have a higher water use efficiency and productivity than C3 crops. C4 crops have a competitive advantage over C3 crops under conditions of drought, high temperatures and nitrogen limitations. With the exception of a small number of C4 species native to cool climates, most C4 species are of tropical or subtropical origin and do not achieve high productivity in cool temperate areas due to delayed canopy development and impaired photosynthesis at low temperatures. C4 crops that are used for energy purposes include maize, sorghum, sugarcane and switchgrass.

The water use efficiency of a specific crop also vary with climate, growing period and agronomic practice and – as mentioned earlier – there are several options for modification of the water use efficiency. There is a highly dynamic relationship between plant growth and water productivity (particularly in tropical regions) in agricultural systems currently experiencing low yield levels (Rockström 2003, 2007). Improvements in agricultural productivity (i.e., yield levels) will also raise water productivity.

Second, the share of the aboveground biomass growth that is usable as feedstock in the electricity/biofuels production varies between crops and conversion technologies. For example, in prospective technologies where biomass is gasified and subsequently synthesized to gaseous (methane, DME) or liquid (FT-diesel, methanol) biofuels, most of the aboveground biomass can be used. This is also the case when solid biomass is used for electricity generation. But when ethanol is produced from sugarcane or sugar beet, only the sugar in the crops is presently used as feedstock, corresponding to about 25 percent of aboveground sugarcane growth and about 40 percent of sugar beet whole-plant mass. When ethanol is produced from cereals such as wheat or corn, only the grain is presently used, which usually makes up less than half the aboveground biomass. Similarly, the extraction of vegetable oil from oil seeds, or from the fruit of the oil palm tree, leaves a large part of the aboveground biomass unused (from the perspective of biodiesel production).

[10] And also substantial CO_2 emissions from the deforestation, that can more than outweigh the climate benefit of the production and use of crops for energy purposes.

Thus, in many instances less then half of aboveground growth is usable as feedstock when biofuels are produced from these crops. The use of harvest residues and processing by-flows for the production of additional biofuels and electricity can reduce the water intensity substantially. For example, sugarcane-ethanol factories use the bagasse, which is obtained as a by-flow, 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. The excess electricity can be exported to the grid, which leads to that the total bioenergy output (ethanol and electricity) per unit sugarcane ET increases, i.e. the water intensity is reduced.

The water intensity might also be considered as being reduced when residues and by-flows are used for non-energy purposes such as animal feed, since they replace other water using production. However, the water savings may take place far away from the biofuel producing regions, such as when protein rich processing by-flows from biofuel production in Europe replace soybean imports from Brazil.

Third, the conversion efficiency varies substantially among the different electricity and biofuel options.

The low case for energy crop ET in Table 1 combine the highest crop water use efficiency data found in a literature survey with technology options having conversion efficiencies in the upper range of what is found in literature, and where harvest residues and process by-products are used for energy purposes. The high case in Table 1 combine the lowest water use efficiency data from the literature survey with technology options having lower conversion efficiencies and where no harvest residues or process by-products are used for energy.

It should be noted that the numbers in Table 1 shows the ET per unit of *gross* bioenergy output. The ET per unit of *net* output would be higher and it would increase differently for different bioenergy routes since they differ in their requirements of energy inputs in feedstock production and conversion to biofuels. The multitude of possible configurations available for the different bioenergy systems (including various polygeneration options, by-product uses, the possibilities of co-siting with other industrial applications and infrastructure providing heat sinks/sources, etc.) and the variety of methodological approaches for estimating net energy outputs for bioenergy systems prevents a condensed summary of the issue in this report[11].

Table 1. Energy crop ET per unit bioenergy feedstock production and per unit gross bioenergy production. Based on (Berndes, 2002). Additional data can be found in Appendix A.

[11] An extensive number of reports and scientific articles are available. For a brief account of the issues involved, see Berndes et al. (2008).

Biofuel	Feedstock	Energy crop ET[a]			
		(ton water per GJ of feedstock)		(ton water per GJ of gross electricity or biofuel output)	
Traditional food crops		Low case	High case	Low case	High case
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	200	40	351
Lignocellulosic crops[b]		7	68		
Ethanol				11	171
Methanol				10	137
Hydrogen				10	124
Electricity				13	195

[a] Lower range numbers refer to systems where: (i) harvest residues from non-lignocellulosic crops (50 percent of total amount of residues) are used for power production at 45 % 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 system designs allowing for export of electricity in excess of internal requirements.

[b] For example short rotation woody crops such as willow and Eucalyptus and grasses such as Miscanthus and Switchgrass.

5 Water implications of bioenergy expansion strategies

As Table 1 clearly showed, the water use implications of bioenergy expansion strategies depend on which bioenergy routes (including crop choice) that become dominating. It also depends on the geographic distribution of the expansion and which lands that become appropriated for the energy crop production. Below, two examples of global/regional bioenergy expansion pathways are presented: (i) near/medium term, focusing on national transport sector targets for selected major countries/regions, relying on biofuels from conventional food crops, (ii) longer term, including bioenergy for both transport and stationary uses (heat and power), mainly based on lignocellulosic crops and related conversion technologies.

5.1 Expanded production of biofuels for transport based on conventional food crops

Under strategies that focus on biofuels for transport and mainly lead to increased cultivation of conventional agricultural food/feed crops (such as cereals, oil crops and sugar crops) for the production of so-called 1st generation biofuels for transport, the increasing global water use will resemble that driven by increasing food sector demand. However, the geographical

pattern may be different since the demand for biofuels for transport may be geographically differently distributed than the increasing demand in the food sector.
Figure 8 illustrates the crop harvest increase required in the countries of the world if a future supply of 1st generation biofuels were to grow to a level corresponding to 20% of the motor fuel consumption in 2005[12]. Countries close to the diagonal line would roughly have to double their crop harvest in order to support such a level of biofuels use, based on domestic feedstocks. Countries far above the line would require less relative increase in harvest, but this does not necessarily mean that they would be able to supply all the required feedstocks domestically: Figure 8 merely indicates the required effort in the agricultural sector and should be complemented with information about the availability of not yet utilized land and water resources, considering also the expected increase in food demand in the coming decades (Figure 5). In addition, as will be discussed in the subsequent Section, technology development might bring about biofuels for transport based on lignocellulosic sources (e.g., forest wood, agricultural harvest residues and lignocellulosic crops) and biomass may also be used for heat and power production, increasing demand further.

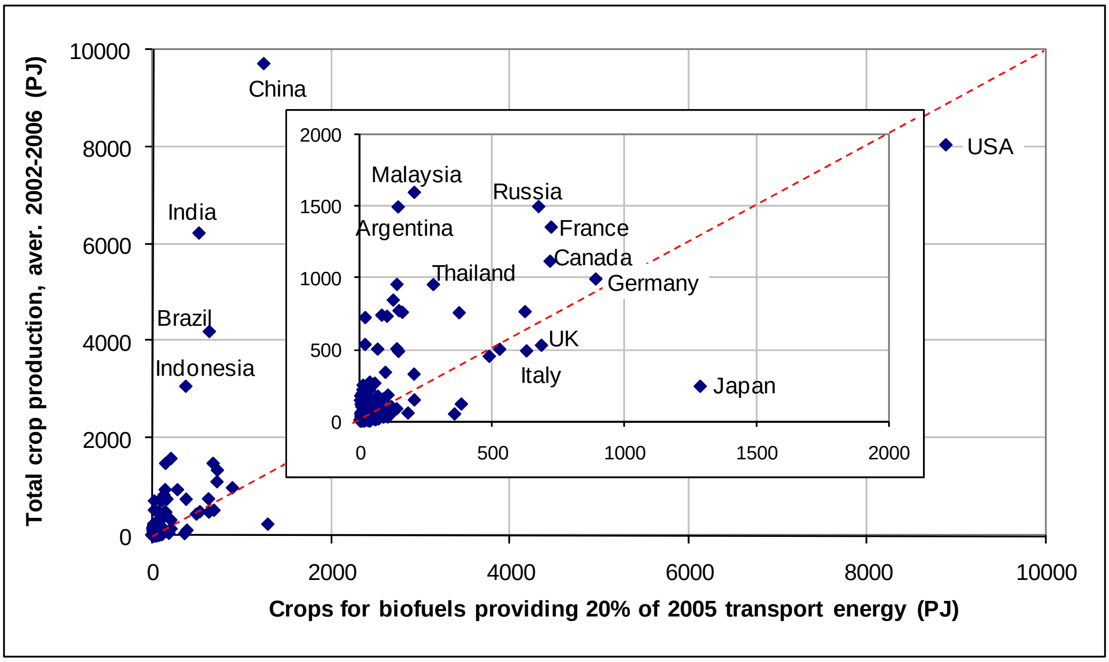

Figure 8. An illustration of the crop harvest required for 1st generation biofuels to make a substantial contribution in the world. The y-axis shows the average 2002-2006 domestic production of food and feed crops and the x-axis shows the amount of crops needed as feedstock for the production of 1st generation biofuels corresponding to 20 % of domestic transport fuel consumption in 2005. The red diagonal represents the situation where a country would have to double the domestic crop production in order to reach the 20 % biofuels share. It is assumed that the biomass is converted into biofuels at an average efficiency of 50 % (energy

[12] This can be compared with for instance (i) the minimum target of 10% for use of biofuels in transport in the EU to be reached by 2020; (ii) the biofuel goal for 2030 set by the Congress-established Biomass Research and Development Technical Advisory Committee – to displace petroleum corresponding to 30% of the present petroleum consumption in the USA; and (iii) the 10% targets in Japan (by 2008) and Thailand (by 2012). See (OECD 2007) for a review of policy measures supporting production and use of bioenergy.

basis). The inset smaller diagram is an enlargement of the lower left part of the larger diagram. Based on (FAOSTAT 2008, IEA 2006).

Insights into the land and water use implications of an expanding agricultural production for both biofuels and food in a selection of major regions and countries can be obtained from Fraiture et al. (2008), which combined specific biofuel expansion pathways with the base food scenario developed for the Comprehensive Assessment of Agricultural Water Management (CA). Fraiture et al. (2008) consider biofuel contributions to transport fuel supply that is in line with IEA (2004) and Rosegrant et al. (2006). Globally, the biofuels share reaches 7.5% of total gasoline demand by 2030; a near quadrupling relative to their base year 2005.

Table 2 summarizes the results for 2030. As can be seen, at a global level the additional demand for the biofuels feedstocks is small in comparison to projected food and feed demand. While some areas may face water and land limitations, others have sufficient spare capacity, provided that the modelled productivity improvements materialize: the optimistic scenario used assumes a combination of strategies to meet food demand while minimizing additional water requirements. Those strategies include improving rainfed agriculture through better rainwater management, improving yields and water productivity on existing irrigated areas, and expanding irrigated areas and trade, according to regional strengths and limitations.

Fraiture et al. (2008) placed special focus on China and India and conclude that the strain on water resources in these countries might make policy makers hesitant to pursue biofuel options, at least those based on traditional field crops. Given the small share of water use modelled to become dedicated to the production of biofuel crops, this illustrates the state of water in these countries. The authors find it unlikely that fast growing economies such as China and India will be able to meet future food, feed and biofuel demand without substantially aggravating already existing water scarcity problems – or importing grain and/or biofuels. In other regions/countries such as EU and Brazil water constraints is reported to be less of a problem.

Table 2. Biofuels contribution and related land and water use in 2030. Based on (Fraiture et al., 2008).

	Biofuel share of transport fuels 2030	Biofuel option	Feedstock production: Absolute (Mton) and compared to production of the same crop for food and feed in 2030	Share of total cropped area for biofuels	Share of total crop ET for biofuels	Share of total irrig. withdrawals for biofuels
USA, Canada	5%	Corn ethanol	(131) +42%	9%	11%	20%
EU	10%	RME	(51) +242%	28%	17%	1%

China	9%	Corn ethanol	(45) +26%	4%	4%	7%
India	10%	Cane ethanol	(101) +16%	1%	3%	5%
Africa	2%	Cane ethanol	(20) +70%	small	12%	30%
Brazil*	65%	Cane ethanol	(384) +75%	7%	14%	8%
Indonesia	2%	Cane ethanol	(9) +21%	small	1%	7%
World	7.5%			3%	3%	4%

* Mainly South Africa

For most countries/regions considered in Fraiture et al. (2008) the biofuels production corresponds to rather low levels of bioenergy supply – at least considering the fossil fuel substitution requirements for reaching stringent climate targets. Since only Brazil was assumed to export substantial quantities of biofuels, countries that have relatively low projected gasoline consumption in 2030 also need to produce relatively small biofuel volumes.

Given the high oil prices and related economic effects, countries in e.g., Africa may chose to rely on biofuels to a higher degree than suggested in IEA (2004) and Rosegrant et al. (2006). Furthermore, together with other tropical regions Africa is commonly suggested to become a major biofuel supplier on a prospective global biofuel market. Thus, it is well motivated to investigate the consequences of substantially larger biofuel production levels than those analysed by Fraiture et al. (2008) – in Africa as well as other tropical regions.

Figure 9 shows the ET from biofuel feedstock cultivation year 2030 in the different countries at different levels of biofuels production (10-50 percent of projected domestic transport fuel use in 2030). Besides showing how the ET from biofuel feedstock cultivation grows as the biofuels share increases, Figure 9 shows how large part of the total crop ET (biofuel feedstock + food) in the country year 2030 that is related to the biofuel feedstock cultivation. Figure 9 illustrates the water implications of the countries providing all biofuel feedstocks based on domestic cultivation. As can be seen, there are large differences between the countries what regards how an expanding biofuel production would add to the total ET in agriculture. The major reason is of course that the projected transport fuel use in 2030 varies very much. For instance, USA & Canada are together projected to use roughly 50 percent more transport fuels than all the other countries taken together and more than four times as much as China. It should be noted here that Africa corresponds to mainly South Africa, due to restricted data availability.

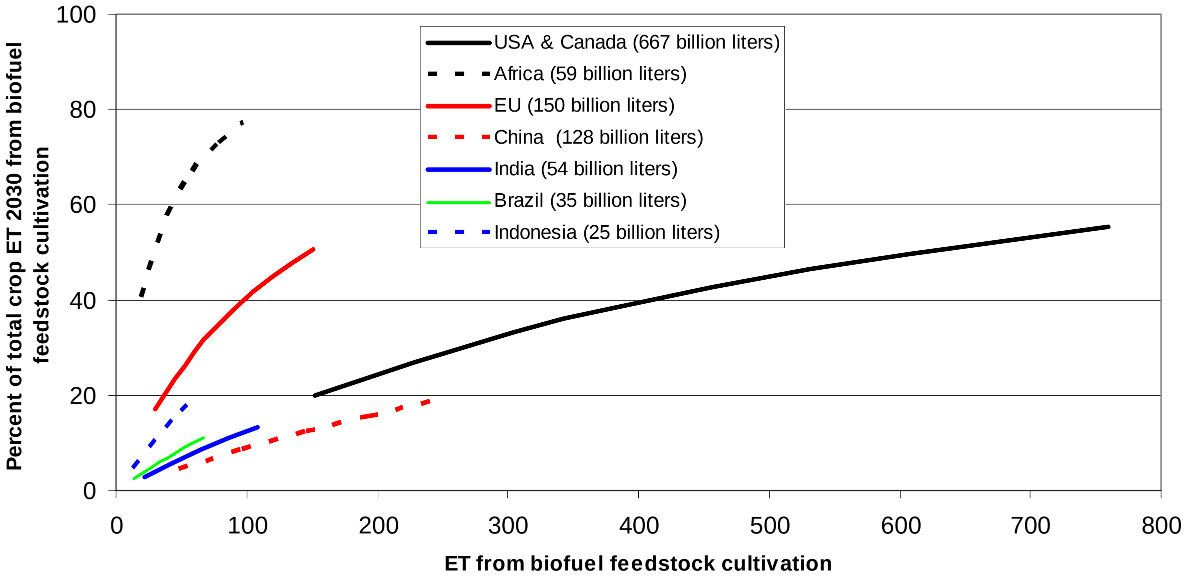

Figure 9. ET from biofuel feedstock cultivation in the selected countries/regions, to support a domestic biofuels production equaling 10 percent (lower end) to 50 percent (higher end) of projected transport fuel use in 2030. Based on country/region-specific water intensity of biofuel routes as in Fraiture et al. (2008). The crop ET in 2030 is estimated from the WATERSIM model (Fraiture 2008). The projected transport fuel use in 2030 (IEA 2005) is presented in the legend to the right of each country/region. Africa is mainly South Africa.

Using the same indicators as in Figure 9 above, Figure 10 is indicative of the water implications of the different countries providing substantial volumes of biofuels on a prospective global biofuels market year 2030: the countries/regions are assumed to provide 25% of the global biofuel demand and the ET linked to biofuel feedstock cultivation is shown for different levels of global biofuels demand, ranging from 10 to 50% of the projected global transport fuel use in 2030. Here, the difference in how far the countries/regions move towards the right is indicative of the water intensity of the respective biofuel routes (see Table 2). Once again, Africa corresponds to mainly South Africa.

Figure 9-10 clearly show the agricultural ET consequences of a possible stronger expansion of biofuel production than that explored by Fraiture et al. (2008). But it is not sufficient for making any clear cut conclusions about the feasibility of large scale biofuel production in the different countries investigated. For this, a comparison with the water resource base is required. For instance, three-quarters of African countries are expected to experience unstable water supplies, where small decreases in rainfall induce much larger reduction in streamflow (de Wit and Stankiewicz 2006). The effects of extensive bioenergy plantations on water use and water balance will be critical to the management of agricultural landscapes and water catchments.

A comparison with the water resource base is made in the following Section where the implications of large scale bioenergy for water use and availability is further elaborated.

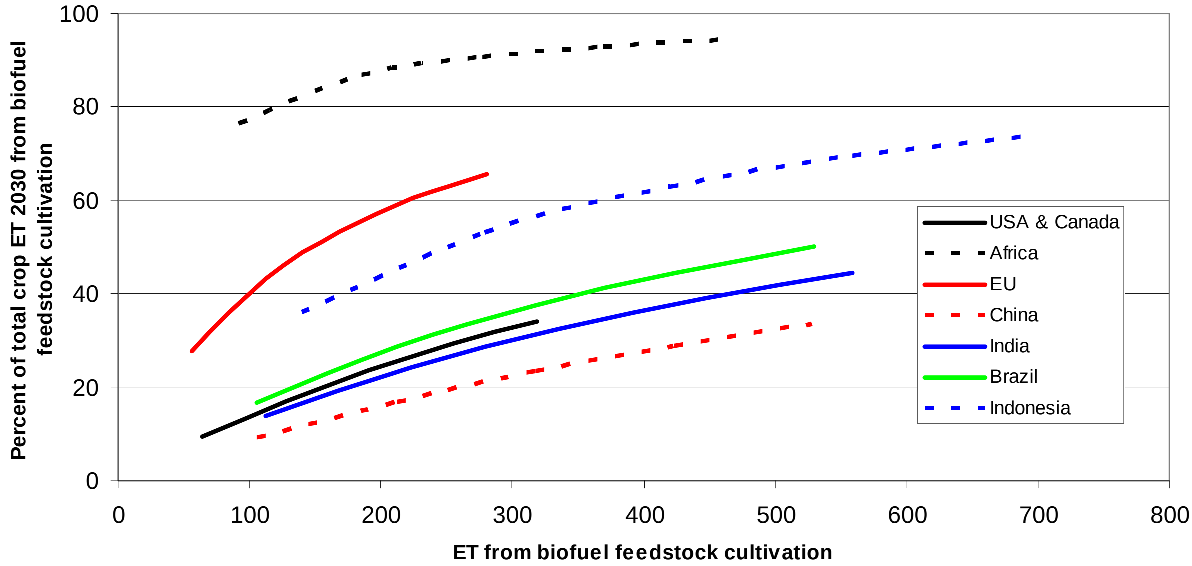

Figure 10. ET from biofuel feedstock cultivation in the selected countries/regions, to support a domestic biofuels production corresponding to 25 percent of the global biofuels use, as the biofuels share increases from 10 percent (lower end) to 50 percent (higher end) of projected transport fuel use in 2030. The country/region-specific average energy crop ET is kept constant for the total range of biofuel production level, making ET from biofuel feedstock cultivation growing proportionally with the biofuels production volume. See Figure 9 Caption for additional information on calculation procedure and data sources.

5.2 Expanded production of biofuels and electricity based on lignocellulosic crops

This section provides illustrative calculations of water implications of a large scale bioenergy expansion. Future bioenergy demand cannot be straightforwardly forecasted – especially not over the longer term – and the calculations should not be regarded as projections of the future state of bioenergy and related water use implications. They rather serve the purpose of linking possible scales of bioenergy with water use and availability in different world regions.

Figure 11 indicates the level of ET from the energy crop production that is required to supply the biomass used for energy in six global energy scenarios. They represent widely different futures (see Figure 11 Caption) but common to all the scenarios is that the global biomass demand for the production of commercial energy carriers (such as electricity and alcohols) grows over time, although at quite different rates: it ranges from 47 to 123 EJ/yr in 2050 and from 157 to 304 EJ/yr in 2100. These bioenergy demand levels do not reflect potential biomass availability but rather the competitiveness of bioenergy against other energy options given a certain development of population and economic activity – and the energy intensity of the economic activities. Also, assumptions about policy regime and development of bioenergy and other energy technologies, is crucial for how the demand for bioenergy develops.

The global average energy crop ET is set to 25 tons of water per GJ feedstock (see Table 1 for comparison). The estimated present global cropland ET (including weeds and vegetation in open drainage ditches, green enclosures, and wind breaks) is included in Figure 11 for comparison (Rockström et al. 1999). The energy crop ET will, of course, be lower if residues and process by-flows from the food and forest sector provide a share of the biomass supply for energy. If, for example, residues contributed 25 percent, then the curves in Figure 11 would be 25 percent lower.

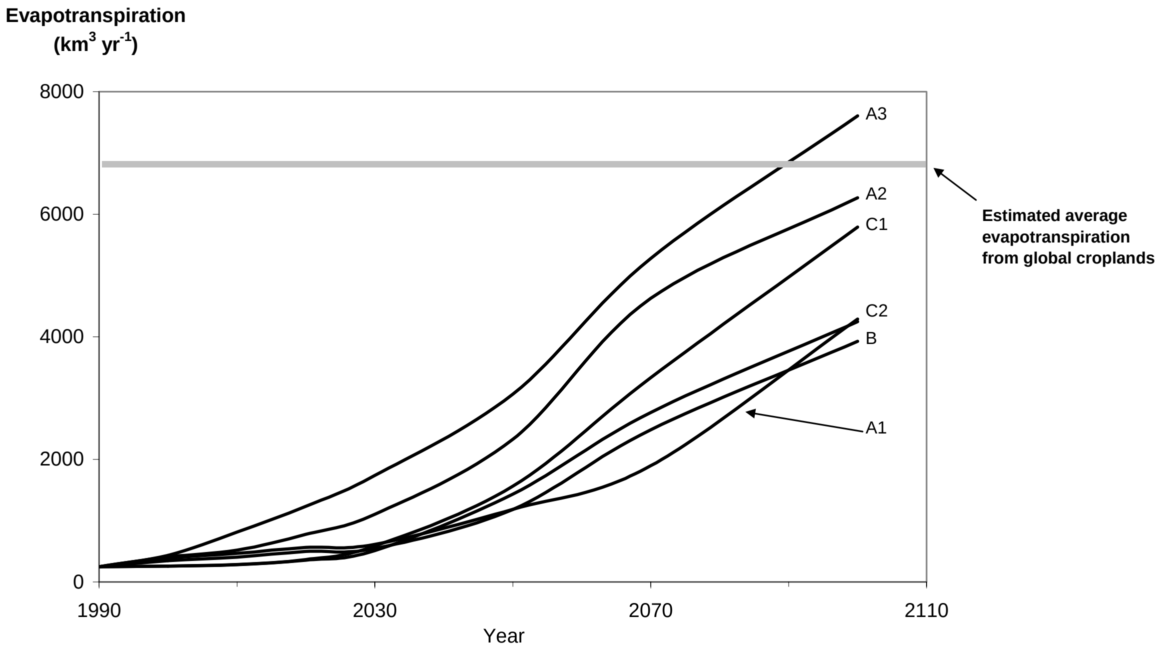

Figure 11. ET from energy crops production in the six global energy scenarios, and estimated ET from global cropland (Berndes 2002). The three "high growth" A scenarios range from assuming that high availability of oil and gas resources leads to dominance of oil and gas until the end of the 21st century (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 outcompeted (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 about technology development while emphasizing international cooperation and equity and also environmental protection. C1 assumes a complete phase-out of nuclear power, while C2 assumes nuclear expansion.

In order to indicate the implications for water use and availability, the A3 scenario above – reaching a biomass demand at about 300 EJ in 2100 – is combined with a food sector scenario including modelling of the long term water use and availability. The bioenergy sector is assumed to influence water use and availability in two ways:

- (Case 1) by withdrawing water for irrigation of energy crops: 15% of crop ET is assumed to be met by irrigation at 50% efficiency, increasing the total withdrawals. The rainfed energy crop production is assumed not to reduce water availability in this case;

- (Case 2) by increasing the ET on the land where energy crops are established: the redirection of rainfall from runoff and groundwater recharge to ET is assumed to reduce downstream water availability by an amount corresponding to one third of energy crop ET.

Water availability is here defined as the sum of modelled river runoff and groundwater recharge. The regional A3 scenarios are scaled down to a country by country basis, e.g., Argentina is assumed to produce bioenergy on a per capita basis which corresponds to the per capita bioenergy demand in Latin America as a whole.

Figure 12 shows the results for selected countries within the context of two frequently used indicators: (i) The water barrier concept (Falkenmark 1989) where countries are classified based on the per capita water availability (see Figure 12 Caption); and (ii) The use-to-resource ratio where use refers to water withdrawals and resource refers to water availability. The filled dots in Figure 12 represent the situation in 1995. Arrows originate from each dot and point to the situation in the year 2075, according to the two cases (hollow dots). The hollow dot that is furthest towards the y-axis represents Case 2 where water availability is reduced. The other hollow dot (reaching the furthest upward) represents Case 1 where water is withdrawn for energy crop irrigation. Note that the water uses in other sectors increase as well, and the per capita water availability changes due to population growth and climatic change.

As can be seen from Figure 12, water availability appears not to impose a constraint on the assumed level of bioenergy production in countries such as Canada, Brazil, Russia and Indonesia. However, South Africa, 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. Finally some countries, such as the USA and Argentina, are projected to join the group of countries that withdraw more than 25 percent of available water.

The likelihood of Case 2, where establishment of bioenergy plantations resulted in increased ET leading to reduced downstream water availability, depends on which types of energy crops become dominating and also on which vegetation types become replaced by the energy crops. Compared to food crops, shrubs and pasture vegetation, bioenergy plantations can have higher productivity and higher transpiration and rainfall interception, particularly for evergreen species. Expanding such fast growing plantations on cropland, shrublands or pastures will therefore often lead to increases in ET and reductions in streamflow.

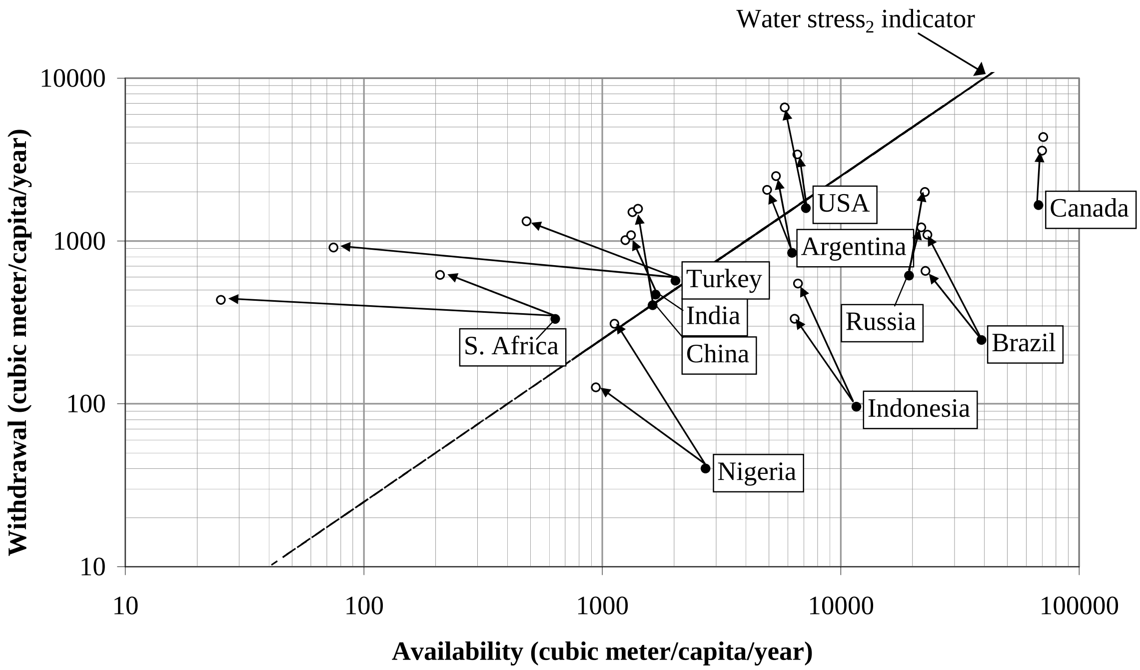

Figure 12. Per-capita water withdrawal and availability for a selection of countries in the scenario. Filled dots represent the situation in 1995. The water availability is given along the x axis. Below 500 m3 cap^{-1} a country faces absolute water scarcity, between 500 and 1000 m3 cap^{-1} water scarcity, and between 1000 and 1700 m3 cap^{-1} water stress. Countries having more than 1700 m3 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 percent. This line is designated Water stress$_2$ threshold following (Raskin et al. 1995).

Indications of possible water availability implications of large scale bioenergy plantations can be obtained from Jackson et al., (2005) that made a global analysis of 504 annual catchment observations, reporting 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. These observations indicate that a reduction in runoff can be expected with afforestation of grasslands and shrublands. In some locations, such as parts of Australia where increased ET can ameliorate salinity and groundwater upwelling, plantations may bring a positive change (discussed further in a later Section). In many other regions, reduced runoff will cause or intensify water shortages.

Similar indications are obtained from (Zomer et al., 2006) that made 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 elsewhere for other uses. This was particularly evident in drier areas, the semi-arid tropics, and in conversion from grasslands and subsistence agriculture.

Thus, it can be concluded that if plantation establishment on abandoned agricultural land and sparsely vegetated degraded land becomes one major option for a large-scale bioenergy expansion, the water use dimension of expanding such bioenergy needs to be carefully investigated. Beyond water, it may also be noted that while many highly productive lands have low natural biodiversity, the opposite is true for some marginal lands and, consequently, the largest impacts on biodiversity could occur with widespread use of marginal lands. This observation provides another challenge for the suggestion that large-scale expansion of bioenergy crops could avoid competition with food by focusing on marginal lands – not least since the lower productivity implies larger land requirements for a given biomass output.

6 Water resource management

6.1 Blue/green water strategies

Understanding opportunities for more efficient water resource management requires that a distinction is made between the blue water flow – the runoff in rivers, lakes and groundwater aquifers, which is supported by 30-40 percent of the precipitation – and the green water flow that sustain the terrestrial ecosystems that produce food and other biomass and a range of other ecosystem services. The fraction of rainfall that infiltrates through the land surface and forms soil moisture is the green water resource (Figure 13).

Society can store blue water and divert it to different uses through technical means. It is the source of water to households, industry, services and irrigated agriculture. Blue water also plays a key role in the generation of ecosystem services. The management of the green water resource is different. Since the green water resource cannot be redirected, technical interventions to manage and augment the green water resource focus on enhancing infiltration potential and local storage of rainwater or run-off. Land management systems are an important part of a green water strategy, as infiltration and storage within the soil profile can be dramatically changed through land use practices.

To ensure efficient management of both green and blue water resources, it is crucial to recognise these functions and to manage them in an integrated manner. However, in terms of attention and investments, the blue water resource has received a larger share of international efforts to develop and manage water resources. If similar attention and investments would be given to the management of the green water resource, the pending water crisis in many parts of the world could be mitigated by broadening the range of livelihood options. Noting that regions such as Africa and Latin America commonly are suggested to become major biofuel suppliers on a prospective global biofuel market – usually with reference to land rather than water abundance – the investigation of blue/green water strategies integrating the possibility to cultivate also bioenergy crops are much motivated.

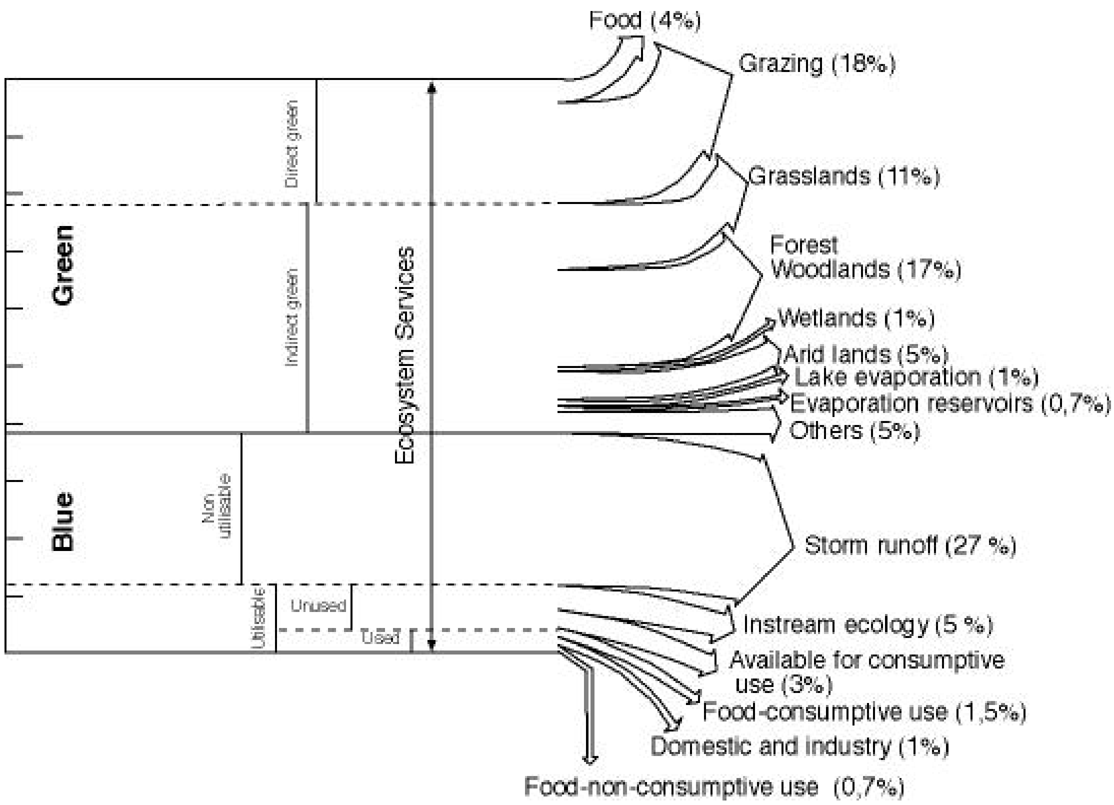

Figure 13. The partitioning of global rainfall (Falkenmark and Rockström 2004). Examples of points for closer investigations include: (i) the intensification of animal production, leaving room for bioenergy plantations on pastures and thus channelling part of the green water flow on pastures (grazing) to energy crop ET, and (ii) strategies to redirect part of the storm runoff productive ET, where suitable energy crops may offer an important option.

Large yield variability in sub-humid and semi-arid regions of the world indicates an opportunity for increasing food production through improved water and land management. There are several options for improving the yields, such as changing sowing date and plant density, modifying nutrient management practices, supplemental irrigation and microclimate manipulation. Due to denser canopies and improved shading of the soil as a result of higher yields, water productivity improves simultaneously, constituting a win-win situation between water and yield (productivity) as well as livelihoods (Figure 14).

This effect is most pronounced at low yields around 1 ton per hectare, which is common in large parts of sub-Saharan Africa. Looked at from another perspective, low yields in sub-humid and semi-arid regions of the world indicates an opportunity for increasing food production while at the same time improving water productivity. In addition, evaporation losses in irrigation systems can be substantially reduced, allowing for increasing the biomass production without extracting more water from rivers, lakes and wells. On average, about 40 percent of the applied irrigation water is transpired by the crop. Although, not all unproductive irrigation water is lost to evaporation and downstream re-use of irrigation water "lost" to run-off improves the irrigation water use efficiency on the basin level.

Given that several types of energy crops are perennial leys and woody crops grown in multi-year rotations, the increasing bioenergy demand may actually become a driver for land use shifts towards land use systems with substantially higher water productivity. Longer growing seasons imply larger seasonal ET – i.e., increased water use – but also higher yields. A prolonged growing season may facilitate a redirection of unproductive evaporation and runoff to plant transpiration, and crops that provide a continuous cover over the year also conserve soil by diminishing the erosion from precipitation and runoff outside the growing season of annual crops[13].

Research has shown that agroforestry can increase water productivity by decreasing the proportion of unproductive rainfall, which would otherwise be lost as runoff or soil evaporation (Ong et al., 2006). For example, intercropping Grevillea robusta with maize in semi-arid Kenya doubled overall rainfall utilization. In Kenya, the use of deciduous trees helps smallholders optimize water supplies while harnessing new economic products (Muthuri et al., 2004).

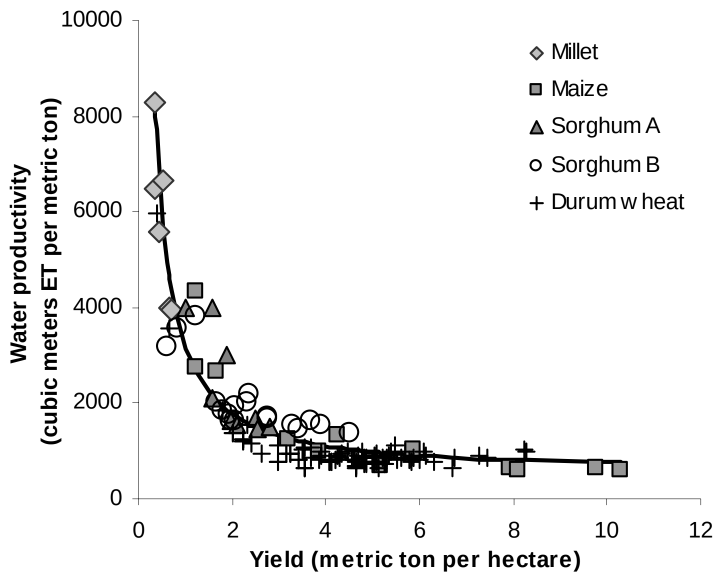

Figure 14. Yields and water productivity for selected crops grown under varying condition. As yields improve water productivities improve simultaneously, constituting a win-win situation between water and yield. Based on (Rockström et al. 2007)

[13] Cynara is, for example, a perennial plant suited to the dry Mediterranean conditions. It can take advantage of winter rains and produce high yields without irrigation, in contrast to crops like Miscanthus and sorghum, which require irrigation for high yields under such conditions.

Since a number of crops that are suitable for bioenergy production also are drought tolerant and relatively water efficient there are clear options to ease competition for water and the pressure on other land-use systems: in addition to providing an option for climate change mitigation, bioenergy may become valuable for strategies to *adapt* to climate change in agriculture, i.e. to cope with a change in precipitation patterns and increased rates of ET due to higher temperature. At the same time, this possibility to integrate the cultivation of new types of bioenergy crops within agricultural systems in a modified water context presents also challenges in the development of land use strategies: plantations of fast-growing trees can exacerbate water shortages and changes in water and land management and use will have an impact on downstream users and ecosystems (e.g. Calder, 1999; Perrot-Maître and Davis, 2001). From a regional development perspective it is important to probe into the complementarities and trade-offs between green and blue water. A successful green water strategy may reduce the blue water resource and, hence, be a constraint to activities that rely on this part of the water resource.

6.2 Land and water productivity in livestock production

The crop dimension of water resource management strategies needs to be complemented with a discussion of livestock production. As indicated in Figure 13, ET on permanent pastures and other grazing land account for the largest share of the water used in the food and agriculture system. Despite this, relatively little attention has been paid to increasing water productivity on grasslands, largely due to a prevailing notion that this water has no alternative uses and therefore has little opportunity cost (e.g. Steinfeld et al. 2006, CA 2007). However, this notion may largely be attributed to the state of affairs in the pre-climate change era. As has been argued earlier in this report, in an increasingly carbon-constrained economy, biomass – and consequently water and land – will have an increasingly higher opportunity cost, related to its higher value as an energy source.

As was shown in an earlier Section, there are great opportunities to increase feed-to-food conversion efficiencies in animal food production, leading to increases in water productivity and thus a decoupling of water from animal food production[14]. In addition (as was also noted), large pastures could become available for other uses, possibly bioenergy plantations that could contribute considerable volumes of biomass for energy without claiming land beyond what has already been appropriated in agriculture.

In their comprehensive review of livestock-environment interactions, Steinfeld et al. (2006) concluded that a principle means of limiting livestock’s environmental burden must be to reduce its land requirements and the implicit water use represented by the land. One of the

[14] Readable studies of long-term development of feed-to-food efficiency of animal food production include Bouwman et al. (2005), CAST (1999), de Haan et al. (1997), Delgado et al. (1999), Keyzer et al. (2005), Steinfeld et al. (2006).

key strategies is intensification of the more productive grassland areas, including improving pasture yields and intensifying production, and the retirement of marginal land from livestock production. Substantial livestock water productivity gains can also be obtained from better integration of crop and livestock in mixed systems (Steinfeld et al. 2006).

Options that augment overall water productivity on land that has earlier been considered as virtually without opportunity cost are increasingly relevant. Thus, faster growth in livestock productivity, combined with a transition from low-intensive grazing over vast grassland areas towards mixed farming and improved pastures with higher yields, has the potential to substantially increase water productivity of animal food production, while allowing for substantial biomass production for energy on part of formerly extensive grazing land[15]. The integration of sugarcane cultivation with livestock production is one example of an option to increase water productivity of permanent pastures. Preliminary case study analyses for Brazil indicate that the increased water productivity is not only due to that sugarcane is produced on the pasture land but also due to that the integration strategy induces productivity increases of the previously extensive milk production (Sparovek et al. 2007).

Once again, these opportunities – attractive when assessed only from a land resource perspective – need to be carefully assessed from a water balance perspective. Recalling the results reported by Jackson et al. (2005) and Zomer et al. (2006), intensive bioenergy production on formerly rather low productivity pastures may lead to negative outcomes for water.

6.3 The use of degraded and marginal lands for bioenergy production

Biomass plantations can be established on degraded or otherwise marginal land, where production of food crops is not economically viable. It has been suggested that by targeting such land, farmers could avoid/mitigate competition with food and also restore soil organic matter and nutrient content, stabilize erosion and improve moisture conditions. In this way an increasing biomass demand could become instrumental in the reclamation of land that has been degraded from earlier over-exploitation and improper management.

The establishment of suitable bioenergy crops on degraded lands may also be an opportunity for increased use of green water flows by shifting vapour flows on degraded lands to productive transpiration of the bioenergy crops. Such strategies could allow for the reclamation of degraded land and enhanced biomass production without necessarily compromising downstream blue water resources, hence mitigating both land and water competition. Jatropha is one example of a crop that is promoted as a water efficient crops that can be grown on dry and semi-arid conditions. India has launched programs to introduce Jatropha which is to be planted on about 13million hectares, mainly on the so-called

[15] The replacement of extensive livestock production with bioenergy is already seen, for instance in Brazil where sugarcane plantations are commonly established on pastures.

‘wastelands’ (Rajagopal 2008). If successful, such biofuel schemes may make a positive contribution to environmental rehabilitation by reducing soil erosion and the removal of soil nutrients. At the same time, little is known of the potential hydrological impacts of large scale conversion of barren land into Jatropha plantations in India which will increase crop transpiration, infiltration, shading, but decrease soil evaporation. A possible reduction of downstream water availability may become an unwelcome effect requiring management of trade-off between upstream benefits and downstream costs.

In addition to recalling the need of integrated basin analysis to understand the possible effects of using degraded land for bioenergy on downstream water users and ecosystems, it should be noted that some studies indicate that biomass production on marginal/degraded land may not be the automatic outcome of increasing biomass demand. As bioenergy use increases and farmers adopt the bioenergy crops, they will consider the development in both food and bioenergy sectors when planning their operations. The economic realities at the farm level may then still lead to that bioenergy crops compete with food crops, since it is the good soils that have the higher yields also for the bioenergy crops[16]. The cultivation costs are lowest on the best soils and highest for the poorest soils when costs for land are excluded. Crop prices are reflected in land prices and in a situation where prices for conventional crops are low, the higher yields on better soils outweigh the increased (land) cost of shifting cultivation from poorer to better soils. An increase in food crop prices will produce a movement for these bioenergy crops in the direction of poorer soils. If the prices for the bioenergy crops increase more than food crop prices, this will cause a movement of lignocellulosic crops to better soils.

Thus, biomass plantations may eventually be pushed to marginal/degraded land due to increasing land costs following increased competition for prime cropland, but this competition will likely also be reflected in increasing food commodity prices.

Rules and regulations may dictate that certain bioenergy crops should be produced on certain soils not suitable for food/feed crops production (such as wastelands in India) or on lands where the cultivation of food/feed crops causes too large environmental impacts (such as sloping erodible soils on the Loess Plateau in China). Regulations may also prevent that farmers use more than a certain share of their land for energy crops production.

7 Opportunities for meeting a growing bioenergy demand while promoting sustainable land and water management

This report focuses on bioenergy and water links. However, the complexity and interconnected nature of environmental and socio-economic problems implies that strategies

[16] Studies discussing food-bioenergy competition include Azar and Berndes 1999, Azar and Larson 2000, Johansson and Azar 2007, McCarl and Schneider 2001, Sands and Leimbach, 2003

based on a holistic perspective are needed: a too narrow focus on one problem at a time can at worst make another problem even more serious, or at best prevent taking advantage of potential synergy effects. Biomass production for energy is a good example of where a holistic perspective must be adopted: the production of biomass can also yield significant additional (positive and negative) environmental effects in connection with changing how land is used in forestry and agriculture. Based upon general and local knowledge of possible feedbacks and integration between technical, social and ecological systems, it is possible to find different ways of producing biomass while generating additional benefits, including the provision of specific environmental services and also increased water productivity in agriculture.

Multifunctional biomass production systems can – through well-chosen localization, design, management and system integration – offer extra environmental services that, in turn, create added value for the systems. The systems can be divided roughly into two categories. Some are exploited for directed environmental services, an example being when trees are established as a wind break to reduce wind erosion. Others are systems that provide environmental services of more general nature, for instance soil carbon accumulation leading to improved soil fertility and enhanced climate benefit.

While the concept of multifunctional biomass production systems might appear a recent invention, the underlying idea – that certain plants can be cultivated in certain ways to provide various benefits in addition to the harvest – has probably always influenced land use strategies. Specifically for lignocellulosic crops, integration of different perennial grasses and short rotation woody crops has been suggested as a way of remediating many environmental problems, including biodiversity loss. A brief survey of some specific applications of multifunctional biomass production systems is given below.

Plantations can be used as ***vegetation filters for the treatment of nutrient-bearing water*** such as wastewater from households, collected run-off water from farmlands and leachate from landfills. Plantations can also be located in the landscape and managed for capturing the nutrients in passing run-off water. Sewage sludge from treatment plants can also be used as fertilizer in vegetation filters. Plantations can also reduce direct surface runoff, trap sediment, enhance infiltration and reduce the risks of shallow landslides. Besides the on-site benefits of ***reduced water erosion***, there are also off-site benefits such as reduced sediment load in reservoirs, rivers and irrigation channels.

Plantations established as ***wind breaks can reduce wind erosion*** that cause soil productivity losses and lower crop yields. These plantations also provide wind shelter and shade for livestock on farms – and even provide supplementary fodder. There are also reductions of off-site impacts on health of particulate pollution and less cost in the form of cleaning, maintenance and replacement expenditures.

The clearing of native vegetation for pastures and agriculture can lead to rising water tables due to lower ET of the new vegetation. Salt moving into the surface soils can make large areas less suitable or even unusable for agriculture (Anderies 2005). In such situations, ***plantations can be established for salinity management***: vegetation with high water usage can be planted to intercept water moving through the soil and reduce groundwater recharge. There are different ways to combine this function with engineering strategies for lowering the water table in salt affected areas. When planted up slope of salt prone areas, high water use crops contribute to preventing salinity by reducing the amount of water reaching the recharge zones. When planted within salt prone areas, high water use (saline tolerant) crops can lower the water table and also reduce evaporation losses by proving ground cover. To be of environmental benefit it is critical that planting of SRC are strategically located so as to reduce saline groundwater movement whilst minimizing use of fresh water (Pannell et al. 2004).

By replacing annual crops with multi-year plantations, the working of the land decreases greatly and the supply of organic material to the soil increases. This leads to ***increases in the soil carbon content and improved soil productivity*** (until a new equilibrium is reached after some decades, where the supply and breakdown of organic material balance each other). There is also an enhanced climate benefit since the soil carbon is fixed from the atmosphere, and the average amount of standing biomass increases.

In addition to degradation processes leading to soil productivity losses, an increasing amount of agricultural land is contaminated by anthropogenic pollutants. Cadmium accumulation in arable soils is one specific example of soil degradation, which has received considerable attention due to possible direct environmental effects (risks for soil living organisms and thereby important soil functions such as nitrogen fixation) and health risks associated with exposure of humans to cadmium through agricultural products (renal dysfunction and possible brittleness of the bones). ***Plantations of suitable species can be used to remove cadmium and other heavy metals from cropland soils*** (Berndes et al. 2004). For example, certain willow clones are very efficient at accumulating heavy metals – notably cadmium but also, to some degree, zinc – which are then removed from the field with the harvest. The cadmium uptake in willow can be up to 40 times higher than in cereal crops.

Integration of specific biomass plantations in the agricultural landscape can increase biodiversity and animal life. ***Plantations can be located in the agricultural landscape as ecological corridors*** that provide a route through which plants and animals can move between different spatially separated ecosystems, and reduce the barrier effect of agricultural lands. The positive effect on opportunities for hunting is now also beginning to be noticed in Sweden: an investigation shows that about 40% of the Swedish cultivators would consider growing willow partly or solely for the wild game's sake (Berndes and Börjesson, 2004).

Research in Sweden and elsewhere has shown that the environmental benefits from a large-scale establishment of multi-functional biomass production systems could be substantial.

Given that suitable mechanisms to put a premium on the provided environmental services can be identified and implemented, additional revenues can be linked to biomass production systems and this could enhance the socioeconomic attractiveness and significantly improve the competitiveness of the produced biomass on the market. The provision of additional environmental services also contributes to local sustainable development, which is in many cases a prerequisite for local support for the production systems.

Figure 15 exemplifies the Swedish case, where inventories of the potential for willow plantations delivering specific environmental services have found that an estimated 50 000 hectares could be dedicated to multifunctional willow plantations providing environmental services having an estimated economic value exceeding the total cost of willow production. On more than 100 000 hectares, the biomass could be produced in plantations providing environmental services having an estimated value above, or roughly equal to, half the biomass production cost. The production and use of biomass from multifunctional biomass production systems would not only contribute to the development towards more sustainable energy systems, but also to development towards a more sustainable agriculture and to increased recirculation and efficiency in societal use of essential resources such as phosphorus and other nutrients. This way, multifunctional biomass production systems may become a valuable tool also for meeting additional great challenges such as getting the world's water cleaner and preserving the long-term quality of agricultural soils.

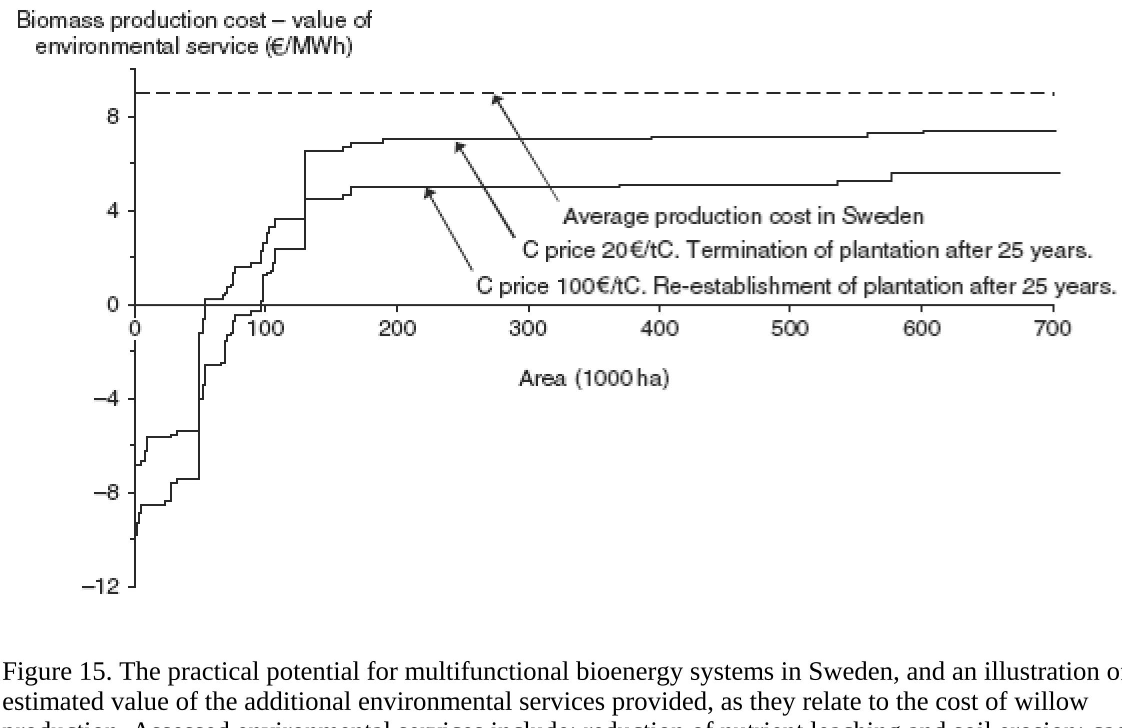

Figure 15. The practical potential for multifunctional bioenergy systems in Sweden, and an illustration of the estimated value of the additional environmental services provided, as they relate to the cost of willow production. Assessed environmental services include: reduction of nutrient leaching and soil erosion; cadmium removal from agricultural land; increased nutrient recirculation and improved treatment efficiency of nutrient-rich drainage water and pre-treated municipal wastewater and sludge; and provision of habitats and contribution to enhanced biodiversity and game potential Source: (Berndes and Börjesson 2004, Berndes et al. 2004, Börjesson and Berndes 2006). Reproduced by permission of ETA-Florence/WIP-Munich.

8 Summary with conclusions for sustainable bioenergy and sustainable water resource management and an account of research needs

The quantifications in this report have served the purpose of relating a prospective bioenergy sector with the food and forest sectors and with global and regional land and water resources. While these quantifications clearly show that bioenergy may place a great new demand for land and water, the report has also maintained that growing bioenergy demand may be instrumental in promoting more sustainable land and water uses around the world: besides providing an option for climate change mitigation, bioenergy may be an option for adaptation to climate change.

Several examples have been given of opportunities and trade-offs of different land-use and management options for food and bioenergy production, with indications of research needs for supporting rational decisions and implementation of efficient policies. One example of a window of opportunity is that a number of crops that are suitable for bioenergy production are drought tolerant and relatively water efficient crops that are grown under multi-year rotations. These crops provide an option to improve water productivity in agriculture and help alleviate competition for water as well as pressure on other land-use systems. It also offers a possibility to diversify land use and livelihood strategies and protect fragile environments.

In this context, the development of technologies for producing second generation biofuels from lignocellulosic feedstocks is one crucial determinant of development opportunities. *Firstly*, they can use a range of agricultural and wood-related residues as their feedstock without any direct claims on land or water. *Secondly,* the land use efficiency of second generation biofuels based on lignocellulosic crops is commonly substantially higher than that of 1^{st} generation biofuels[17], leading to less land required per unit of energy produced. *Thirdly*, a wider spectrum of land types could be available for the feedstock cultivation. Notably pastures and grasslands, not viable for first generation biofuels due to environmental and greenhouse gas implications (intensive soil management leads to soil carbon losses as CO_2), could become an additional resource for high-yielding lignocellulosic feedstocks under suitable management practices. Marginal areas could also be considered for lignocellulosic feedstock production.

The notion about large areas of pastures/grasslands and marginal/degraded lands being available for lignocellulosic crop production must however be verified in relation to water

[17] For example, cereal ethanol and biodiesel from rape seed. The sugarcane ethanol option offers very high land use efficiency, which could improve further as technologies eventually become available that makes it possible to use also the bagasse for ethanol eventually become available. Bagasse is the cellulosic residue that is obtained from the conventional ethanol production from the sugar.

availability and use. To assess the impact of land and water use and management, an integrated basin analysis is required; however, this is rarely done today (Rockström et al., 2007). The impact of energy crops on changes in hydrology needs to be researched in order to advance our understanding of how the changes in water and land management will affect downstream users and ecosystems (Uhlenbrook 2007). In many cases such impacts can be positive. For example, local water harvesting and run-off collection upstream may reduce erosion and sedimentation loads in downstream rivers, while building resilience in the upstream farming communities. Conversely, the use of marginal areas with sparse vegetation for establishment of high-yielding bioenergy plantations may lead to substantial reductions in runoff, which can be positive or negative depending on specific context.

The cultivation of less ‘thirsty’ trees can decrease the impact of climate change and drought and provide benefits for farmers, and there is a need to identify more deciduous species. Current research involves identifying the tradeoffs on the water use and water balance of trees that have implications for water management, forestry and agroforestry, especially in semi-arid and arid regions.

Some evidence suggests that on a continental scale, forests may form part of a hydrological feedback loop with ET contributing to further rainfall. The effects of forests on rainfall cannot be totally dismissed, but are likely to be relatively small. Nevertheless, considering the prospects for extensive reforestation – e.g., of pastures – for the purpose of providing biomass for energy (or carbon sinks), further research to determine the magnitude of the effect is warranted; particularly at the regional scale (Rockström et al 1999, Gordon et al. 2005, Uhlenbrook 2007).

To the extent that large areas of marginal lands are available, research and development of crops and cultivation systems to obtain lower production costs on these marginal lands – and also optimum yields in relation to the local/regional water context – could mitigate the bioenergy/food competition by reducing the price level on prime cropland where it becomes most attractive to shift to cultivating suitable energy crops on the marginal lands.

Although it is widely believed that opportunities exist to improve water productivity in animal food production, the overall knowledge of livestock water productivity is poor (CA 2007). There are few reliable estimates of livestock productivity for ruminant production systems, partly due to their large diversity and large uncertainties in the water productivity of forage crops and grasslands. The knowledge gap is particularly large for developing countries, and impedes the introduction of targeted measures that could bring about significant gains in water productivity (CA 2007). Therefore, it is crucial to acquire improved knowledge of the potentials for increased livestock water productivity, and how they can be realized.

9 References

Aden, A; Ruth, M.; Ibsen, K.; Jechura, J.; Neeves, K.; Sheehan, J.; Wallace, B.; Montague, L.; Slayton, A.; and Lukas, J. (2002). Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis for Corn Stover. NREL report NREL/TP-510-32438. 2002.

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.

Anderies, J.M. (2005). Minimal Models and Agroecological Policy at the Regional Scale: An Application to Salinity Problems in Southeastern Australia. Regional Environmental Change 5 (1): 1–17.

Azar, C. and Berndes, G. (1999) The implication of CO2-abatement policies on food prices. In: Sustainable Agriculture and Environment: Globalisation and trade liberalisation impacts (Eds, Dragun, A. and Tisdell, C.) Edward Elgar: Cheltenham, UK.

Azar, C. and Larson, E. D. (2000) Bioenergy and land-use competition in Northeast Brazil, Energy for Sustainable Development, 4, 64-71.

Berndes, G. (2002). Bioenergy and water -the implications of large-scale bioenergy production for water use and supply. Global Environmental Change 12(4):7-25.

Berndes, G., Fredriksson, F. and Börjesson, P. (2004). Cadmium accumulation and Salix based phytoextraction on arable land in Sweden. Agriculture, Ecosystems and Environment 103(1): 207-223.

Berndes, G. and Börjesson, P. (2004). Low cost biomass produced in multifunctional plantations –the case of willow production in Sweden. 2nd World Conference and Technology Exhibition on Biomass for Energy, Industry and Climate Protection, Rome, Italy, 10-14 May 2004.

Berndes, G. (2006). The contribution of renewables to society. In: Dewulf, J. and Van Langenhove, H. (eds.). Renewables based technology. John Wiley & Sons, Ltd. London, UK.

Börjesson, P. and Berndes G. (2006). The prospects for willow plantations for wastewater treatment in Sweden. Biomass and Bioenergy 30: 428-438.

Berndes, G., Börjesson, P., Rosenqvist, H. and Karlsson, S. (2008). Bioenergy: Resource efficiency and contributions to energy and climate policy goals. An overview commissioned by the Swedish Energy Agency.

Bouwman, A.F., Van der Hoek, K.W., Eickhout, B., Soenario, I. (2005). Exploring changes in world ruminant production systems. Agricultural Systems 84(2), 121-153.

BP (2007). Statistical review of world energy 2007. (http://www.bp.com/statisticalreview)

Bruinsma, J. (ed.) (2003). World agriculture: towards 2015/2030. An FAO perspective. Food and Agriculture Organization (FAO)/Earthscan Publications, Rome/London.

CA (2007): Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture. D. Molden (ed.), Earthscan, London and International Water Management Institute, Colombo.

Calder, I.R. (1999). The Blue Revolution: Land Use and Integrated Water Resources Management. London: Earthscan.

Carlsson-Kanyama, A. (1998). Climate change and dietary choices - how can emissions of greenhouse gases from food consumption be reduced? Food Policy 23(3-4), 277-293.

Carlsson-Kanyama, A., Ekstrom, M.P., Shanahan, H. (2003). Food and life cycle energy inputs: consequences of diet and ways to increase efficiency. Ecological Economics 44(2-3), 293-307.

CAST (1999). Animal agriculture and global food supply. Task Force Report 135. Council for Agricultural Science and Technology (CAST), Ames.

de Boer, J., Helms, M., Aiking, H. (2006). Protein consumption and sustainability: Diet diversity in EU-15. Ecological Economics 59(3), 267-274.

de Haan, C., Steinfeld, H., Blackburn, H. (1997). Livestock & the environment: Finding a balance. Food and Agriculture Organization of the United Nations, Rome.

Delgado, C., Rosegrant, M., Steinfeld, H., Ehui, S., Courbois, C. (1999). Livestock to 2020: The next food revolution. Food, Agriculture, and the Environment Discussion Paper 28 International Food Policy Research Institute (IFPRI), Washington.

De Wit M, Stankiewicz J (2006). Changes in surface water supply across Africa with predicted climate change. Science 311: 1917-1920.

DOE (2006). Energy demands on water resources. Report to Congress on the Interdependency of Energy and Water. U.S. Department of Energy, December, 80 pp.

Duchin, F., 2005. Sustainable consumption of food - A framework for analyzing scenarios about changes in diets. Journal of Industrial Ecology 9(1-2), 99-114.

EC (2006) Energy: yearly statistics, 2006 edition. Data 2004. Luxembourg: Office for Official Publications of the European Communities.

Elferink, E.V., Nonhebel, S., (2007). Variations in land requirements for meat production. Journal of Cleaner Production 15(18), 1778-1786.

Falkenmark, M., (1989). The massive water scarcity now threatening Africa: why isn't it being addressed? Ambio 18 (2), 112–118.

Falkenmark, M., and J. Rockström. (2004): Balancing Water for Humans and Nature: The New Approach in Ecohydrology. London: Earthscan.

FAOSTAT (2008). FAO online statistical databases. http://faostat.fao.org/ UN Food and Agriculture Organization, Rome.

Fraiture, C. de, Wichelns, D., Kemp Benedict, E. and Rockström, J. (2007). Scenarios on water for food and environment. Chapter 3 in Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture. Earthscan, London, UK and Colombo: International Water Management Institute, Colombo, Sri Lanka.

Fraiture, C. de, Giordano, M. and Yongsong, L. (2008). Biofuels and implications for agricultural water use: blue impacts of green energy. Water Policy 10 Supplement 1. pp. 67-81.

Gerbens-Leenes, P.W., Nonhebel, S., (2002). Consumption patterns and their effects on land required for food. Ecological Economics 42, 185-199.

Gerbens-Leenes, P.W., Hoekstra, A.Y., Van den Meer, TH.H. (2008). Water footprint of bio-energy and other primary energy carriers. Value of Water Research Report Series No. 29. UNESCO-IHE, Institute for Water Education.

Goldemberg, J. (2000). World Energy Assessment: Energy and the Challenge of Sustainability. UNDP / UN-DESA / World Energy Council.

Goldemberg J. and Johansson T.B. (2004). World Energy Assessment Overview: 2004 Update. UNDP, UN-DESA and the World Energy Council.

Gordon, L., Steffen, W., Jönsson, B., Folke, C., Falkenmark, M. and Åse Johannessen (2005). Human modification of global water vapor flows from the land surface. PNAS Vol 102, No 21, pp 7612-7617.

Hoffert, M., Caldeira, K., Jain, A., Haites, E., Harvey, L., Potter, S., Schlesinger, M., Schneider, S., Watts, R., Wigley, T. and Wuebbles, D. (1998). Energy implications of future stabilization of atmospheric CO2 content. Nature 395, 881-884.

Hoffert, M., Caldeira, K., Benford, G., Criswell, D., Green, C., Herzog, H., Jain, A., Kheshgi, H., Lackner, K., Lewis, J., Lightfoot, H., Manheimer, W., Mankins, J., Mauel, M., Perkins, L., Schlesinger, M., Volk, T., Wigley, T. (2002). Advanced Technology Paths to Global Climate Stability: Energy for a Greenhouse Planet. Science 298 (5595) 981-987.

IEA (2004). Biofuels for transport. An International Perspective, OECD/International Energy Agency, Paris, France.

IEA (2005). Advanced Motor Fuels. Annual Report. OECD/ International Energy Agency, Paris, France.

IEA (2006). Energy Balances of OECD Countries (2006 edition)--Extended Balances; Energy Balances of Non-OECD Countries (2006 edition)--Extended Balances. International Energy Agency (IEA) Statistics Division, Paris. Available at http://data.iea.org/ieastore/default.asp.

Jackson, R. B., Jobbágy, E. G., Avissar, R., Roy, S. B., Barrett, D. J., Cook, C. W., Farley, K. A., le Maitre, D. C., McCarl, B. A., and Murray, B. C. (2005). Trading water for carbon with biological carbon sequestration. Science 310(5756): 1944-1947.

Johansson, D. and Azar, C. (2007). A scenario based analysis of land competition between food and bioenergy production in the US. Climatic Change, 82 (3-4) pp. 267-291.

Keeny, D. and Muller, M. (2006). Water Use by Ethanol Plants: Potential Challenges. Institute for Agriculture and Trade Policy, October 2006.

Keyzer, M.A., Merbis, M.D., Pavel, I.F.P.W., van Wesenbeeck, C.F.A. (2005). Diet shifts towards meat and the effects on cereal use: can we feed the animals in 2030? Ecological Economics 55(2), 187-202.

Lundqvist, J., Barron, J., Berndes, G., Berntell, A., Falkenmark, M., Karlberg, L., and Rockström, J. (2007). Water pressure and increases in food & bioenergy demand: implications of economic growth and options for decoupling. In: Scenarios on economic growth and resource demand. Background report to the Swedish Environmental Advisory Council memorandum 2007:1.

Muthuri CW, Ong CK, Black .R, Mati BM, Ngumi VW, Van-Noordwijk M. (2004). Modelling the effects of leafing phenology on growth and water use by selected agroforestry tree species in semi-arid Kenya. Land Use and Water Resource Research 4: 1-11.

McCarl, B. A. and Schneider, U. A. (2001) Greenhouse gas mitigation in US agriculture and forestry, Science, 294, 2481-2482.

OECD (2007). A review of policy measures supporting production and use of bioenergy. OECD, Trade and Agriculture Directorate, Committee for Agriculture. TAD/CA/APM/WP 2007/24.

Ong CK., Black CR., Muthuri CM. (2006). Modifying forestry and agroforestry to increase water productivity in the semi-arid tropics. CAB reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources no.065.

Pacala, S. and Socolow, R. (2004). Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies. Science 305 (5686) 968-972.

Pannell, D. J., Ewing, M. A. And Ridley, A. M. (2004), Dryland salinity in Australia: Overview and prospects. In: Grahan,T. W., Pannell, D. J. And White, B. (eds.) Dryland Salinity: Economic Issues at Farm, Catchment and Policy Levels. Co-operative Centre for Plant-Based Management of Dryland Salinity, University of Western Australia. pp. 3-18.

Pate, R., M. Hightower, C. Cameron, and W. Einfeld. (2007). Overview of Energy-Water Interdependencies and the Emerging Energy Demands on Water Resources. Report SAND 2007-1349C. Los Alamos, NM: Sandia National Laboratories.

Perrot-Maître, D., and P. Davis. (2001). Case Studies: Developing Markets for Water Services from Forests. Washington D.C.: Forest Trends.

Pielke, R., Wigley, T. and Green, C. (2008). Dangerous assumptions. Nature 452, 531-532.

Phillips, S., A. Aden, J. Jechura, D. Dayton, and T. Eggeman. (2007). Thermochemical Ethanol via Indirect Gasification and Mixed Alcohol Synthesis of Lignocellulosic Biomass. Technical Report NREL/TP-510-41168. Golden, CO: National Renewable Energy Laboratory.

Rajagopal, D. (2008). Implications of India’s biofuel policies for food, water and the poor. Water Policy 10(S1): 95- 106

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

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.

Rockström, J. (2003). Water for food and nature in the tropics: vapour shift in rainfed agriculture. Phil. Trans. R. Soc. Land B. 358:1997-2009.

Rockström, J., Lannerstad, M., Falkenmark, M. (2007). Assessing the water challenge of a new green revolution in developing countries. PNAS 104, 6253-6260.

Rockström, J., Hatibu, N., Oweis, T.Y., Wani, S., Barron, J., Bruggeman, A., Farahani, J., Karlberg, L. and Qiang, Z. (2007). Managing water in rainfed agriculture. In: D. Molden (ed.). Comprehensive Assessment of Water management in Agriculture. 2007. Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture. London: Earthscan, and Colombo: International Water Management Institute.

Rosegrant, M. W., Msangi, S., Sulser, T. & Valmonte-Santos, R. (2006). Biofuels and the global food balance. In: Bioenergy and Agriculture: Promises and Challenges. FOCUS 14. International Food Policy Research Institute, Washington, DC.

Sands, R. D. and Leimbach, M. (2003) Modeling agriculture and land use in an integrated assessment framework, Climatic Change, 56, 185-210.

Sims, R., Schock, R., Adegbululgbe, A., Fenhann, J., Konstantinaviciute, I., Moomaw, W., Nimir, H., Schlamadinger, B., Torres-Martínez, J., Turner, C., Uchiyama, Y., Vuori, S., Wamukonya, N. and Zhang, X. (2007). Energy supply. In Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Metz, B., Davidson, O., Bosch, P., Dave, R. and Meyer, L. (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Smil, V. (2002). Worldwide transformation of diets, burdens of meat production and opportunities for novel food proteins. Enzyme and Microbial Technology 30(3), 305-311.

Sparovek, G., Berndes, G., Egeskog, A., Luiz Mazzaro de Freitas, F., Gustafsson, S., Hansson, J. (2007). Sugarcane ethanol production in Brazil: An expansion model sensitive to socioeconomic and environmental concerns. Biofuels, Bioproducts and Biorefining, 1: 270-282.

Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V., Rosales, M., de Haan, C. (2006). Livestock's long shadow: Environmental issues and options. Food and Agriculture Organization of the United Nations (FAO), Rome.

Takada, M. and Porcaro, J. (2005). Achieving the Millennium Development Goals: The role of energy services - case studies from Brazil, Mali and the Philippines. UNDP/BDP Energy and Environment Group.

Uhlenbrook, S. (2007). Biofuel and water cycle dynamics: what are the related challenges for hydrological processes research? Hydrological Processes, 21, 3647–3650.

UNDP (2005). Energizing the Millennium Development Goals: A Guide to Energy's Role in Reducing Poverty. UNDP/BDP Energy and Environment Group.

WHO (2002). The World Health Report 2002. World Health Organization, Geneva.

Wirsenius, S. (2003a). The biomass metabolism of the food system: A model-based survey of the global and regional turnover of food biomass. Journal of Industrial Ecology 7 (1): 47-80.

Wirsenius, S. (2003b). Efficiencies and biomass appropriation of food commodities on global and regional levels. Agricultural Systems 77 (3): 219-255.

Wirsenius, S., Azar, C. and Berndes, G. (2004) Global bioenergy potentials: A new approach using a model-based assessment of biomass flows and land demand in the food and agriculture sector 2030. In: van Swaaij, W. P. M., Fjällström, T. Helm, P. and Grassi, A. (eds.) Second World Biomass Conference: Biomass for Energy, Industry and Climate Protection. ETA-Florence, Florence.

Wirsenius, S., Berndes, G., and Azar, C. (forthcoming). How much land can livestock productivity increases and dietary changes spare for nature? Scenarios of agricultural land use in 2030. Manuscript for submission to Agriculture, Ecosystems & Environment

Zomer, R. J., Trabucco, A., van Straaten, O., Bossio, D. A. (2006). Carbon, land and water: A global analysis of the hydrologic dimensions of climate change mitigation through afforestation/reforestation. Colombo, Sri Lanka: International Water Management Institute. 44p. (IWMI Research Report 101).

Zwart, S.J. and Bastiaanssen, W.M.G. (2004). Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. Agricultural Water Management, Vol. 69(2): 115-133.

Appendix A. Some additional data

Complementary to the ranges for water productivity of different bioenergy options presented in the report, additional data is given in this Appendix.

In Table A1, water productivity (WP) values for different food groups for temperate and tropical regions are presented. These values were collected from literature (Zwarts and Bastiaanssen, 2004; Rockström et al., 1999). For China, an average between temperate and tropical water productivity was used, as the food is produced in varying conditions and intensities. Moreover, in the estimations for China, cereal was sub-divided into a category "all cereals except rice" (WP=1400 m3/t) and rice (WP=3500 m3/t).

The data in Table A1 can be used for calculating the water requirements for both selected biofuel options as well as for specified diets. This allows for own scenario constructions of future food and bioenergy developments.

Table A1. Water productivity for different food groups for temperate and tropical regions. In addition, water productivity for different food groups are presented separately for China.

Food group	Temperate WP (m3/t)	Tropical WP (m3/t)	China WP (m3/t)
Cereal	1300	1500	1400
Starchy roots	300	600	300
Sugar crops	130	130	10
Sugar & sweeteners	130	130	130
Pulses	2500	1700	2500
Treenuts	450	450	450
Oil crops	2000	2300	2000
Veg oil	2500	2500	2500
Vegetables	150	150	150
Fruits	300	250	300
Stimulants	4500	4500	4500
Bovine	30000	20000	25000
Mutton& goat	10000	10000	10000
Pork	10000	10000	10000
Poultry	6000	6000	6000
Meat other	10000	10000	10000
Offals, edible	30000	20000	25000
Animal fats	30000	20000	25000
Eggs	3500	3500	3500
Freshwater fish	8000	8000	8000

Table A2 shows the water footprint (m3/GJ) of different hypothetical bioenergy crops in four different countries, as calculated by Gerbens-Leenes et al. (2008), some of which not commonly mentioned in the context of bioenergy. Rough data on the water footprint for the biofuels that can be produced from the hypothetical crops can be obtained from combining these numbers with conversion efficiencies in the biofuel plants.

Additional crop information is given in Table A3.

Table A2. Water footprint (m3/GJ) for selected hypothetical crops grown in the Netherlands, USA, Brazil and Zimbabwe.

Crop	Netherlands	USA	Brazil	Zimbabwe
Cassava			29,7	204,7
Coconut			48,8	204,7
Cotton		135	95,6	355,6
Groundnuts		57,6	51,4	253,6
Maize	9,1	18,3	39,4	199,6
Miscanthus	19,7	37,1	48,8	63,8
Palm oil and kernels			75,2	
Poplar	22,2	41,8	55	72
Potatoes	20,9	45,8	30,7	64,8
Soybeans		99,3	61,1	138
Sugar beets	13,4	23,3		
Sugarcane		30	25,1	31,4
Sunflower	26,9	60,6	54,3	145,5
Wheat	13,8	84,2	81,4	68,7
Rapeseed	67,3	113,3	205,2	

Table A2.Crop information for crops grown in the Netherlands, USA, Brazil and Zimbabwe.

	Yields (ton/ha) / crop water requirement (mm per growing season)			
Crop	**Netherlands**	**USA**	**Brazil**	**Zimbabwe**
Cassava			13,6 / 304	4,4 / 670
Coconut			10,5 / 1557	2,1 / 1290
Cotton		6,0 / 1011	1,4 / 744	0,5 / 1017
Groundnuts		3,3 / 633	2,3 / 395	0,6 / 649
Maize	12,2 / 416	9,3 / 635	3,1 / 304	0,7 / 498
Miscanthus	18,8 / 628	18,8 / 710	18,8 / 1557	18,8 / 1290
Poplar	17,0 / 628	17,0 / 710	17,0 / 1557	17,0 / 1290
Potatoes	41,6 / 430	43,5 / 691	30,7 / 355	15,9 / 511
Soybeans		2,9 / 710	2,2 / 331	1,6 / 558
Sugar beets	65,2 / 499	50,0 / 666		
Sugarcane		67,8 / 1725	73,0 / 1557	76,5 / 2037
Sunflower	2,5 / 385	1,7 / 604	1,6 / 502	0,7 / 546
Wheat	8,6 / 308	2,8 / 926	1,9 / 639	3,0 / 818
Rapeseed	3,7 / 530	1,6 / 377	1,7 / 770	