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INCREASED BIOFUEL PRODUCTION IN THE COMING DECADE: TO WHAT EXTENT WILL IT AFFECT GLOBAL FRESHWATER RESOURCES?[†]

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ABSTRACT

Irrigated agriculture accounts for 70% of global water withdrawals and therefore contributes substantially to global water scarcity. This article focuses on the impact of the increasing demand for biofuel on global water resources in the coming decade. Based on biofuel production projections for 2008 and 2017, it was estimated that currently around 1% of all water withdrawn for irrigation is used for the production of bio-ethanol, mainly produced from irrigated sugar cane and maize. In 2017 the amount of water to be withdrawn for biofuel production would increase by 74% if agricultural practices remain the same. It is, however, likely that in 10 years the increase will be less, mainly due to crop diversification in favour of rainfed crop species. Even though globally the amount of water withdrawn for the production of biofuels is modest, locally water scarcity problems may worsen due to irrigation of bio-ethanol feedstocks. In this context there is reason for concern in countries with fast-developing economies like India, China, Thailand and South Africa where the growing demand for food and energy causes an increased competition for already scarce water resources. This situation will be aggravated if the projected bio-ethanol production will come from irrigated sugar cane. Copyright © 2009 John Wiley & Sons, Ltd.

KEY WORDS: biofuels; bio-ethanol; irrigation requirements; water resource implications; water scarcity

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RÉSUMÉ

L'agriculture irriguée représente 70% du total des prélèvements d'eau et contribue donc sensiblement à la pénurie mondiale de l'eau. Cet article met l'accent sur l'impact de l'augmentation de la demande de biocarburants sur les ressources mondiales en eau dans la décennie à venir. Sur la base des projections de production de biocarburants publiées par l'OCDE et la FAO pour 2008 et 2017 il a été estimé qu'à l'heure actuelle, environ 1% de l'ensemble des prélèvements d'eau à des fins d'irrigation est utilisé pour la production de bio-éthanol, essentiellement produit à partir de la canne à sucre irriguée et du maïs. En 2017 la quantité d'eau utilisée pour la production de biocarburants va augmenter de 74% si les pratiques agricoles restent les mêmes. Il est toutefois probable que cette augmentation ne soit pas aussi importante, et ce en raison principalement de la diversification des cultures en faveur des espèces de cultures pluviales. Même si globalement les volumes d'eau d'irrigation alloués à la production de biocarburants est modeste, la production de bio-éthanol risque d'accentuer localement les problèmes de rareté de l'eau. Dans ce contexte, la production de biocarburants est un motif de préoccupation pour les pays à économies en développement rapide comme l'Inde, la Chine, la Thaïlande et l'Afrique du Sud où la demande croissante en aliments et en énergie entraîne une concurrence accrue pour des ressources en eau déjà très exploitées. Le cas de la production de

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[†]Dans quelle mesure l'augmentation de la production de biocarburants dans la décennie à venir peut-elle affecter les ressources en eau au niveau mondial?

bio-éthanol à partir de canne à sucre irriguée représente certainement le cas le plus critique.

MOTS CLÉS: biocarburants; bio-éthanol; besoins d'irrigation; implications des ressources en eau; pénurie de l'eau

INTRODUCTION

Since the amount of land and water resources that can be used for agricultural production is limited, there is now a widespread fear that the production of biofuels will have a severe impact on natural resources and food security. It is expected that in the next 10 years the first generation of biofuels, i.e. those produced with conventional technology from crops that also can also be used in the human food chain, will remain much more important than second-generation biofuels. Second-generation biofuel production processes that can convert ligno-cellulosic biomass (from crop residues, grasses and trees grown on marginal land) to produce ''cellulosic'' ethanol are currently under development. It is expected that second-generation biofuel production may contribute to mitigate eventual pressures on natural resources that can be used to produce food, but for the time being these technologies are not yet commercially viable (FAO, 2007), and therefore they have not been taken into consideration in the analysis as presented in this article.

In the article the amount of water that is withdrawn for the production of biofuels is estimated on the basis of production figures as published by the Organization for Economic Cooperation and Development (OECD) and the Food and Agriculture Organization of the United Nations (FAO) in the *Agricultural Outlook 2008–2017* (OECD/FAO, 2008). The findings for the major biofuel-producing countries have been compared with earlier global estimations as done by De Fraiture *et al*. (2008).

IRRIGATED AGRICULTURE

In the second half of the twentieth century, demand for food increased fast due to rapid population growth. This demand could only be met due to massive investments in agriculture that led to the green revolution. Irrigation expansion, combined with increased use of fertilizers, pesticides and improved crop varieties, were at the basis of the green revolution, which resulted in a global food production that outstripped population growth (Figure 1, World Bank, 2007; Molden, 2007).

While the productivity of agriculture grew, world demand for agricultural products slowed down and food prices dropped to historical lows at the beginning of this century. Until recently, it was forecast that future demand for agricultural products would slow down further as a result of decreasing population growth (Bruinsma, 2003). However, due to increasing demand for biofuels, the total demand for agricultural products increased faster than expected. This, combined with supply shortfalls, due to drought and low stocks, changes in exchange rates and implementation of additional border measures, resulted in a dramatic increase in food prices during the period 2005–2008. The influence of these higher prices on world food security and the challenges of climate change and bioenergy were topics of discussion at the High Level Conference on World Food Security held from 3 to 5 June 2008, in Rome, Italy, at which an appeal was put forward by 180 countries to increase agricultural production (FAO, 2008a).

In the past, the increase in agricultural production was for a large part supported by irrigation expansion. Currently, 277 million ha are equipped for irrigated agriculture. Irrigated land equals about 20% of total agricultural land, while providing 40% of all agricultural production and even 60% of global cereal production (Bruinsma, 2003). Since agriculture already accounts for about 70% of the freshwater withdrawals in the world, it is often seen as the main factor behind the increasing scarcity of fresh water. The question seems justified whether there will be sufficient fresh water in the future to satisfy the growing demand for water for agriculture and other needs.

Without accounting for climate change and the production of biofuels, the FAO estimated that in 2030 irrigated production in developing countries would rise by 36% compared to the reference situation around 1998 (Bruinsma, 2003). This increase in production would be possible through both yield increases and an increase in irrigated area of 20%. Furthermore, it was expected that through improved irrigation efficiencies and changes in cropping patterns, the extra amount of water needed would be around 14%. Even though in large areas of the developing

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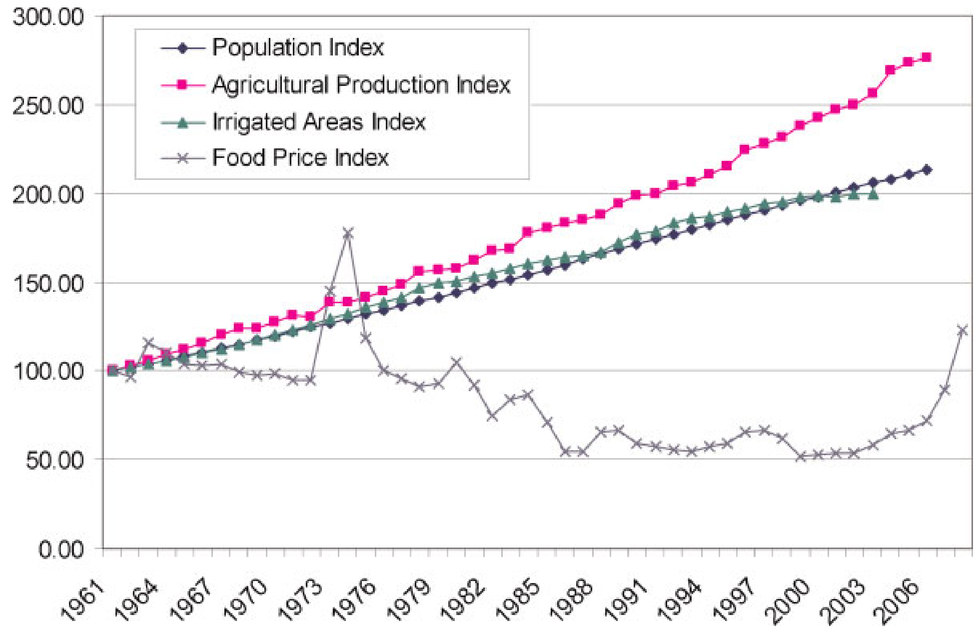

Figure 1. Increases in population, agricultural production and irrigated areas, combined with food prices (all variables are indexed, 1961 = 100). (Source: FAO–FAOSTAT). This figure is available in colour online at www.interscience.wiley.com/journal/ird

world agriculture is facing its limits by either lack of water or lack of land, the result of the assessment was that globally there would be still enough untapped potential to cope with the projected increased demand resulting from population growth and changing diets due to economic growth.

BIOFUELS

Biofuels are sources of energy derived from biological sources (definition according to Uhlenbrook, 2007: ‘‘Fuel with a minimum of 80% content by volume of materials derived from living organisms harvested within 10 years of its manufacture’’). Around 10% of the total primary energy supply comes from biomass (International Energy Agency (IEA), 2007); most of which is used in the form of solid fuel for cooking and heating, especially in developing countries.

Nowadays the term ‘‘biofuels’’ is often used to refer to liquid biofuels used mainly for transport purposes as a replacement for fossil fuels. Production of liquid biofuels for transport is often criticized because it competes with food supply. There is direct competition when edible biomass such as grains, sugar crops, starch crops and oil crops are being used to produce bio-ethanol or biodiesel. Indirect competition also occurs if land that can be used for food production is diverted towards land used for energy crops. As a consequence of this competition, food insecurity for the poor may increase if biofuel production pushes aside food production and prices for agricultural products rise (Brown, 2006; Fresco, 2006; Rosegrant *et al*., 2006; Evans, 2008; FAO, 2008b; Müller *et al*., 2008).

Production of bio-ethanol tripled between 2000 and 2007, with the US and Brazil accounting for the majority of this growth. Biodiesel output witnessed an even more pronounced relative expansion over the same period, having grown from less than 1 billion litres to almost 11 billion litres. The demand for biofuel has increased due to rising oil prices and policies to reduce greenhouse gas emissions. A large number of countries either started or increased renewable energy programmes in the period 2000–2007. Production of liquid biofuels depends very much on governmental support, since the production costs of biofuels are still higher than those of fossil fuels. The only exception is bio-ethanol from sugar cane in Brazil which is competitive with gasoline at a crude oil price of around US$35 per barrel (OECD/FAO, 2008). For reference, crude oil prices were over US$140 per barrel at the end of June 2008.

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Table I. Biofuel projections

	Ethanol production (million litres)		Share of global ethanol production (%)		Energy share in gasoline-type fuel (%)		Biodiesel production (million litres)		Share of global biodiesel production (%)		Energy share in diesel-type fuel (%)	
	2008	2017	2008	2017	2008	2017	2008	2017	2008	2017	2008	2017
USA	38 400	52 400	50	41	4.6	6.0	2 020	1 730	16	7	0.5	0.5
Brazil	22 100	40 500	29	32	40.4	56.6	760	2 520	6	10	1.2	3.6
China	6 690	10 200	9	8	2.0	4.0	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
EU-27	4 400	11 900	6	9	2.2	4.9	6 580	13 300	54	54	3.0	5.0
India	1 910	3 570	2	3	2.7	5.6	317	385	3	2	0.9	0.9
Canada	1 380	2 730	2	2	2.3	4.1	207	660	2	3	1.1	2.8
Colombia	497	796	1	1	5.2	5.0	218	388	2	2	4.0	5.3
Thailand	408	1 790	1	1	2.1	11.7	48	75	0	0	0.0	0.0
South Africa	369	683	0	1	0.0	1.9	0	0	0	0	0.0	0.0
Indonesia	212	227	0	0	0.0	0.0	753	2 990	6	12	0.7	7.9
Vietnam	164	532	0	0	0.0	0.0	0	5	0	0	0.0	0.0
Australia	156	1 000	0	1	0.5	3.3	911	994	7	4	8.2	8.2
Philippines	105	126	0	0	0.7	0.5	0	85	0	0	0.1	0.8
Turkey	77	81	0	0	0.9	1.2	0	0	0	0	0.0	0.0
Malaysia	70	84	0	0	0.0	0.0	443	1 140	4	5	0.4	0.8
Ethiopia	38	74	0	0	0.3	0.7	6	36	0	0	0.2	0.8
Tanzania	29	43	0	0	1.0	2.5	10	53	0	0	0.8	2.6
Mozambique	24	28	0	0	0.3	1.9	3	34	0	0	0.4	2.2
Peru	22	40	0	0	0.2	0.2	0	0	0	0	0.0	0.0
Total	77 100	127 000			5.5	7.6	12 300	24 400			1.5	2.6

Source: OECD/FAO (2008).

Even though the production and use of both bio-ethanol and biodiesel have increased significantly in recent years, they remain modest compared to fossil fuels. It is expected that the energy share of biofuels in transport fuels will grow further in the coming years from 5.5% in 2008 to 7.6% in 2017 for bio-ethanol in gasoline-type fuels and from 1.5% in 2008 to 2.6% in 2017 for biodiesel in diesel-type fuels (Table I) (OECD/FAO, 2008). Global bio-ethanol production is expected to reach more than 125 billion litres in 2017, twice the quantity produced in 2007. Most of the production is projected to originate from Brazil for markets in the EU and the US. Global biodiesel production is set to grow at slightly higher rates than for bio-ethanol to reach some 24 billion litres by 2017. As in the case of ethanol, increased blending mandates should stimulate demand and boost international trade in biodiesel. Most of the trade in raw input material, also referred to as ‘‘feedstock’’, should originate from oil palm plantations in Malaysia and Indonesia with the EU as the main destination (OECD/FAO, 2008).

The projections used in this paper were prepared by the OECD and FAO based on existing biofuel policies. It is, however, not clear that energy security, and the environmental and economic objectives of these policies, will be achieved with current production technologies. Therefore, existing biofuel policies especially in OECD countries should be carefully reviewed on their merits and their unintended consequences (OECD/FAO, 2008). As a result, the projections for future biofuel production as presented here remain uncertain and only give an indication of the amount of biofuels to be produced in the next 10 years.

CROPS USED TO PRODUCE LIQUID BIOFUELS

The most important crops currently used to produce liquid biofuels are sugar cane, sugar beet, maize, cassava, wheat, oil palm, rapeseed and soybean. Sugar cane is the best known crop that is used to produce biofuel, since it is

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used widely in Brazil. Ethanol from sugar cane as produced without subsidies in Brazil is also the only biofuel that is currently competitive with gasoline made from fossil fuel. The largest potential for rainfed production of sugar cane is in the humid (sub-) tropics of South America (Brazil) and in sub-Saharan Africa (Democratic Republic of the Congo) and South East Asia (China). In temperate climate zones, sugar beet is also a crop with potential. Most land potential for rainfed production of sugar beet lies in the USA, Argentina and Europe (from France to Russia) (Fischer *et al*., 2002).

Ethanol can be produced from sugar or starch but it is more efficient to produce it from sugar. Maize starch is the main source for ethanol production in the USA. In the USA, ethanol production benefits from major governmental support. Land potential for maize can be found across the globe where it is both not too wet and not too dry. Winter wheat is used as feedstock for ethanol production in Australia, Canada and in some European countries. Cassava is a tropical root crop with potential to produce ethanol from starch, but it is not yet a major feedstock for ethanol production. It can be found in roughly the same area as sugar cane.

Oil palm is grown in the wettest parts of the tropics. Most of its land potential again lies in the continents of South America and sub-Saharan Africa, and in Malaysia and Indonesia which are at the moment the main palm oil-producing countries. Rapeseed is the most important crop for biofuel in European countries. The European Union set 2010 as the target year that 5.75% of the diesel market should come from biodiesel (European Union (EU), 2003). Like ethanol produced from maize, biodiesel can only be produced from rapeseed in a profitable manner if it is subsidized. Europe, the United States and South America, especially Argentina, have a large land potential to produce rapeseed. Soybean, like maize and rapeseed, is another crop that is not economically profitable for the production of biofuel. However, its common use in the United States for food and feed products has led to soybean biodiesel becoming the primary source for biodiesel.

The crops mentioned are the traditional first-generation biofuel crops. Second-generation biofuels are produced from ligno-cellulosic crops to produce cellulosic ethanol. Crops with potential to produce second-generation biofuels are fast-growing trees like willows, poplar and eucalyptus, and perennial grasses like *Miscanthus* and switch grass. There is great interest in producing cellulosic ethanol, since the aforementioned crops can be grown on marginal land without the need to compete for higher-quality land that can be used for food production. However, second-generation biofuels are not yet commercially viable and it is not clear when all technical barriers can be overcome to make them available on the market, which is the reason why they are not being taken into account in this analysis.

Promising new plant species like jatropha and sweet sorghum have not been taken into account either. Just like the ligno-cellulosic crops, these crops can be grown on poor soils which are less suitable for most food crops. These crops can survive with relatively little water, but their yields are low and major breeding efforts are needed to increase their productivity. For the short-term future it is not expected that these crops will play an important role in terms of bulk volume of biofuels. However, they can become important if they can provide additional income for farmers in semi-arid areas without displacing food crops (Fresco, 2006).

WATER REQUIREMENTS OF BIOFUELS

The impact of biofuel production on land and water resources varies according to climatic and production conditions (Berndes, 2002). Table II lists the yields per crop as well as some indicative figures on their water use. The yields are expressed in litres of fuel per ha and in energy per ha. Biodiesel has a higher energetic density per litre than ethanol (around 35 $MJ\,l^{-1}$ for biodiesel compared to 20 $MJ\,l^{-1}$ for ethanol). The figures listed in Table II refer to evaporation values and indicative yields that can be obtained in countries where biofuels are actually being produced. The figures for bio-ethanol from sugar cane refer to Brazil, while the figures for bio-ethanol from sugar beet refer to France. The yield values are indicative ones taken from different sources (International Energy Agency (IEA), 2004; Marris, 2006; Sims *et al*., 2006; United States Department of Agriculture (USDA), 2006; Mathews, 2007; Naylor *et al*., 2007; Nguyen *et al*., 2007), crop evaporation has been calculated according to Allen *et al*. (1998), and the irrigation water withdrawals were calculated assuming an arbitrary 50% overall irrigation efficiency. It should be noted, however, that yields and water requirements depend very much on

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Table II. Indicative yields and water requirements for some major biofuel crops

Crop	Fuel product	Annual obtainable yield ($l\,ha^{-1}$)	Energy yield ($GJ\,ha^{-1}$)	Potential crop evaporation in mm (indicative)	Evaporation (litre $litre^{-1}$ fuel)	Irrigated or rainfed Production	Rainfed conditions	Water resource implications under irrigated conditions (assuming an irrigation efficiency of 50%)	
							Actual rainfed crop evaporation (in mm, indicative)	Irrigation water used (in mm, indicative)	Irrigation water used (in litre $litre^{-1}$ fuel, indicative)
Sugar cane	Ethanol (from sugar)	6 000	120	1 400	2 000	Irrigated/rainfed	1 100	600	1 000
Sugar beet	Ethanol (from sugar	7 000	140	650	786	Irrigated/rainfed	450	400	571
Cassava	Ethanol (from starch)	4 000	80	1 000	2 250	Rainfed	900	—	—
Maize	Ethanol (from starch)	3500	70	550	1 360	Irrigated/rainfed	400	300	857
Winter wheat	Ethanol (from starch)	2 000	40	300	1 500	Rainfed	300	—	—
Oil palm	Biodiesel	6 000	193	1 500	2 360	Rainfed	1 300	—	—
Rapeseed/ mustard	Biodiesel	1 200	42	500	3 330	Rainfed	400	—	—
Soybean	Biodiesel	450	14	500	10 000	Rainfed	400	—	—

Source: adapted from Müller *et al*. (2008).

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agro-climatological conditions that vary significantly, even within countries. The same applies for the irrigation efficiencies that vary widely depending on irrigation technology and water management practices.

In Table II, some indicative figures are given of the water requirements of some typical crops under the agro-climatic conditions in countries where these crops are being grown for biofuel production. In order to know how the production of biofuels affects water resources in a quantitative sense, it is necessary to know which part comes from irrigated agriculture. Feedstocks for biofuels grown under rainfed circumstances might have an impact on water quality because of the amount of fertilizers and pesticides that may run off to surface and groundwater resources. However, the quantitative impact of rainfed agriculture on water supplies is often negligible and always difficult to assess. It depends on climatic circumstances and on the type of natural land cover occurring if there is no rainfed agriculture. In general it can be stated that in assessing the impact of agriculture on natural resources, land is the distinguishing factor for rainfed agriculture, while water is the most important factor for irrigated agriculture.

Table II shows that, in the described reference situation, it takes around 2000 l of water to produce 1 l of biofuels from sugar cane. The reference situation in Table II refers to obtainable yields in Brazil where sugar cane can be grown under rainfed circumstances. In many other places of the world yields are lower, even when the sugar cane is grown under irrigated circumstances. It is not unrealistic that more than 4000 litres of water needs to be withdrawn for irrigation to produce only 1 litre of ethanol. To put these figures in perspective, these amounts of water are of the same order of magnitude as the water that needs to be transpired by crops to produce the food for one person per day.

Sugar cane is the most widely used crop for production of biofuels. It is also the most water-demanding crop and, therefore, often grown under irrigation. Crops used for the production of biodiesel are hardly ever irrigated. Rapeseed for biodiesel is generally grown in Europe and Canada under rainfed conditions. Oil palm is only grown in the wet tropics without the need for irrigation. Soybean grown in the USA, the only country that uses soybean as a major feedstock for biodiesel, is only irrigated in exceptional cases.

Table III shows which feedstocks are being used for the production of biofuels in the major biofuel-producing countries as listed earlier in Table I. For each country it has been estimated how much water needs to be withdrawn to irrigate these crops for the year 2008 and for the year 2017 under the assumption that agricultural practices do not change in the coming 10 years. The table shows only the water withdrawals for the production of bio-ethanol since, so far, the amount of water withdrawn for the production of biodiesel is assumed to be negligible.

The water withdrawals as presented in Table III have been calculated by applying a spatially distributed water balance over the irrigated areas where crops for biofuel production can be grown. The water demand has been calculated following the guidelines in Allen *et al*. (1998), and was spatially distributed according to the Global Map of Irrigated Areas (Siebert *et al*., 2007, 2005). The tools used were applied earlier to calculate agricultural water demand for the studies *Agriculture towards 2015/2030* (Bruinsma, 2003; Faurès *et al*., 2000) and the first World Water Report *Water for People, Water for Life* (United Nations (UN), 2003). Country data on average irrigation efficiencies, total water withdrawals and total available water resources originate from AQUASTAT, the FAO's information system on water and agriculture. The supply side of the water balance has been taken into account by comparing the agricultural water demand with the total available water resources through an indicator of stress, defined as the ratio of agricultural water demand over the total available water resources. Agricultural water demand, as well as the total available water supply, refers to average climatological and hydrological conditions, not taking into account inter-variability.

From the table it appears that around 1% of all water withdrawn for agricultural purposes is currently used to irrigate feedstocks for biofuels. The figures presented in Table III are of the same order of magnitude as calculations done by De Fraiture *et al*. (2008), but the underlying assumptions are quite different. The study by De Fraiture *et al*. assumes a global bio-ethanol production of 36 800 million litres (around 2004) while this paper assumes 77 000 million litres for 2008. However, the reason for discrepancies between the water withdrawal figures is not due to the differences in production figures but more likely due to the assumptions made on which part of the area under bio-ethanol production is actually irrigated. Statistics on crop yields and areas differentiated for irrigated and rainfed agriculture are not readily available and can often only be estimated on the basis of expert knowledge. This might also explain the large difference in water withdrawn for bio-ethanol in Brazil. De Fraiture *et al*. estimate that in Brazil only 3.5% of water withdrawals are used for the production of bio-ethanol while in this paper a figure of 14% is mentioned. Since this 14% is the largest number in the list, it deserves some explanation. In Brazil, unlike in

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Table III. Implications of bio-ethanol production on water resources per country

	Main feedstock	% of production irrigated	Water demand for ethanol production (km^3)		Total agricultural water withdrawals (km^3)	Irrigation water for biofuel production as percentage of agricultural water withdrawals in 2000		Total available water resources (km^3)	Stress on water resources due to agriculture (%)
			2008	2017	2000	2008	2017		2000
USA	Maize	20	6.21	8.48	198	3	4	3 050	6
Brazil	Sugar cane	15	5.18	9.49	37	14	26	8 230	0
China	Maize	40	7.71	11.78	427	2	3	2 830	15
EU27	Sugar beet/wheat	10/0	0.08	0.21	96	0	0	1,450	7
India	Sugar cane	80	4.18	7.82	558	1	1	1 900	29
Canada	Maize/wheat	35/0	0.20	0.40	5.4	4	7	2 900	0
Colombia	Sugar cane	40	0.21	0.33	4.9	4	7	2 130	0
Thailand	Sugar cane/cassava	65/0	0.80	3.51	83	1	4	410	20
South Africa	Sugar cane	40	0.85	1.58	7.8	11	20	50	16
Indonesia	Sugar cane	100	0.36	0.38	76	0	1	2 840	3
Vietnam	Sugar cane	65	0.28	0.91	49	1	2	891	5
Australia	Wheat/sugar cane	0/65	0.12	0.79	18	1	4	492	4
Philippines	Sugar cane	60	0.05	0.06	21	0	0	479	4
Turkey	Sugar beet	80	0.18	0.19	28	1	1	214	13
Malaysia	Sugar cane	100	0.06	0.08	5.6	1	1	580	1
Ethiopia	Sugar cane	100	0.25	0.48	5.2	5	9	122	4
Tanzania	Sugar cane	100	0.10	0.15	4.6	2	3	96	5
Mozambique	Sugar cane	100	0.04	0.05	0.6	7	8	217	0
Peru	Sugar cane	100	0.08	0.14	16	0	1	1 910	1
Total			26.90	46.80	2 660	1	2	43 700	6

many other countries, sugar cane is mainly grown under rainfed conditions. However, in north-east Brazil, sugar cane is also grown under irrigated conditions. For the calculations it was estimated that 10% of the area under sugar cane was irrigated, which equals 620 000 ha or around 20% of all the irrigated area in Brazil (total irrigated area in Brazil is estimated to be more than 3 million ha, FAO/AQUASTAT). The fact that sugar cane is a very water-demanding crop with a long growing season explains that the percentage of water withdrawn for its irrigation is larger than the percentage of the total area under irrigation. Other countries that withdraw, in absolute terms, much water for production of bio-ethanol are the USA, China and India. For these countries the water withdrawn for biofuel production as a percentage of total irrigation water withdrawals as presented here is comparable to that as calculated by De Fraiture.

In the USA, biofuels are only a marginal additional stress on water supplies at the regional to local scale. However, significant acceleration of biofuel production could cause greater water quantity problems depending on where the crops are grown. Growing biofuel crops in areas requiring additional irrigation water from already depleted aquifers is a concern. The growth of biofuels in the United States has probably already affected water quality because of the large amount of nitrogen and phosphorus required to produce maize. If projected future increases in the use of maize for ethanol production do occur, the increase in harm to water quality could be considerable (Committee on Water Implications of Biofuels Production in the United States, 2008).

In China and India there is reason for concern since in both countries available land and water resources are already scarce (Fischer *et al*., 2002; FAO/AQUASTAT). As shown in Table III, water withdrawals used for irrigation already equal 29% of total available water resources in India and 15% for China. Especially in large countries, national figures mask local realities. China, for example, is very water scarce in the north while the southern part of the country still has abundant water resources. In both countries population and incomes are increasing, resulting in higher food and energy demand. Since land, water and energy resources in China and India are limited, it is likely that both countries will depend more and more on imports from the world market or through trade agreements, rather than producing commodities by themselves. Even though increases in production of bio-ethanol for 2017 of 53% for China and 87% for India are expected, the total amount of water to be withdrawn to irrigate feedstocks for bio-ethanol will remain modest compared to the total amount of water already used for agricultural production.

Table III shows that Thailand and South Africa are also countries with an elevated level of stress on available water resources due to agriculture (20 and 16% respectively). Like China and India, Thailand and South Africa are countries with a steadily growing economy that causes an increasing pressure on scarce water resources. Unlike China and India, however, a substantial increase in bio-ethanol production is projected for Thailand and South Africa. In both countries ethanol is currently mainly produced from sugar cane. If the expected growth in ethanol production is realized under the same agricultural practices as the current biofuel production, both countries will experience a significant additional stress on their water resources. For Thailand the amount of water withdrawn for biofuel production as a percentage of total agricultural water withdrawn in the year 2000, would increase from 1% in 2008 to 4% in 2017. For South Africa these percentages are even higher; 11% in 2008 and 20% for the year 2017.

In Table III it is shown that total expected increase of water withdrawn for bio-ethanol production in 2017 compared to 2008 will be 74%. However, due to the assumption that agricultural practices will not change in the coming 10 years, this value should be considered a worst-case scenario. For several reasons the increase in water withdrawals for the production of biofuels will probably turn out to be lower. Crop production can be increased in three ways: expansion of cultivated land, increasing cropping intensities (shorter fallow periods, and more crops per year), and yield increase. The first two sources of growth in crop production lead to an increase in harvested areas and, if irrigated, would have an impact on the amount of water withdrawn for irrigation. Yield increases obtained on already irrigated land do not generally depend on the total amount of water applied, but are more likely due to higher-yielding crop varieties and better farming practices like optimizing the use of fertilizers and pesticides. In the study *Agriculture towards 2015/2030* (Bruinsma, 2003), the FAO estimates that for the period 1998–2030 the share of growth in crop production that can be attributed to yield increases will be 57%. In the same study, a total annual crop production growth of 1.5% is projected for the period 1998–2015. If 57% of the annual production growth is due to yield increases, this would result in a total production increase of 9% over the period 2008–2017 without the need to apply extra irrigation water.

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Next to expected increases in yields, one can also expect that irrigation efficiency will increase. Since it is already difficult to assess current irrigation efficiencies, it will be even more difficult to predict future irrigation efficiencies. In general one can assume that future irrigation efficiencies will depend on the state of the technology used and the amount of water stress a country has to deal with. One can expect that, under pressure from limited water resources and competition with other users, demand management will play a more important role in improving irrigation efficiency in water-scarce regions than in areas with abundant water. At the same time, improving irrigation efficiency is a slow and difficult process that will become more difficult in areas where efficiencies are already high due to the use of sophisticated irrigation technology.

Crop diversification is the third and most important reason why it is likely that the increase in water withdrawal to irrigate biofuel feedstocks will turn out to be lower than the earlier mentioned 74%. At the moment, sugar cane and maize are by far the most important crops used to produce bio-ethanol, but this is likely to change. Not only because second- generation bio-ethanol from crops grown on marginal lands may become important, but more likely because irrigated sugar cane may be replaced by rainfed crops like cassava or sweet sorghum. For example in Thailand ambitious government plans exist to implement production plants that would use cassava to produce 3.4 million litres of ethanol per day (Nguyen *et al*., 2007). In India and the Philippines, the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) is cooperating with private partners to have commercial bio-ethanol factories running on sweet sorghum (Reddy *et al*., 2005).

DISCUSSION

The growing demand for biofuels affects food security both negatively and positively. It is not completely understood to what extent this demand results in higher food prices. Estimations range from around 3% according to the United States Department of Agriculture (USDA, 2008) to 70–75% according to a Policy Research Working Paper of the World Bank (Mitchell, 2008). At the household level, higher prices for food will have a negative impact on food security for the poor, of which the urban poor will suffer the most. On the other hand new stimuli in the agricultural sector offer new opportunities for rural communities.

At the national level, bio-energy can offer development opportunities for countries with significant agricultural resources. Under the current circumstances only the production of bio-ethanol from sugar cane can compete with the production of gasoline from petroleum. In this context, sub-Saharan Africa and Latin America, with their significant sugar cane production potential, are often cited as regions that could profit from Brazil's experience and technology. Also in terms of land and water availability for irrigated agriculture, both continents are relatively well off (Tables IV and V).

Table III shows that four sub-Saharan African countries already produce bio-ethanol from sugar cane. This may be an indication that the agricultural sector on this continent could benefit from opportunities arising due to increasing demand for biofuels. It should be noted, however, that bio-ethanol produced in these countries originates from large commercial plantations which may help the country in earning some foreign currency, but may not help

Table IV. Freshwater availability and use for agriculture

Region	Renewable freshwater resources		
	Volume (km^3 yr^{-1})	Volume of freshwater used for agriculture in 2000 (km^3 yr^{-1})	Use as % of resources
Sub-Saharan Africa	3 900	97	2
Asia (excl. Near East)	11 100	1 750	16
Near East and North Africa	514	287	56
Latin America and the Caribbean	13 600	187	1

Source: FAO–AQUASTAT.

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Table V. Areas equipped for irrigation in 2003

Region	Irrigation	
	Area (1 000 ha)	As % of cultivated land
Sub-Saharan Africa	7 070	4
Asia (excl. Near East)	171 000	39
Near East and North Africa	28 800	34
Latin America and the Caribbean	18 600	13

Source: FAO–AQUASTAT.

improving livelihoods of the smallholders that make up 99% of the agricultural sector in sub-Saharan Africa (Faurès and Santini, 2008).

The question whether or not there is a dilemma about using biomass for food or fuel production has been debated by many authors (Brown, 2006; Fresco, 2006; De Fraiture *et al*., 2008). Brown (2006) argues that if biomass is used to produce biofuels it will result in less food for the poor. This statement is contested by De Fraiture *et al*. (2008), who argue that malnourishment is due to lack of access to food rather than lack of food supply. Although this is true, the increase in food prices to which increased biofuel production contributes, has a negative effect on the food security situation of urban and landless poor. De Fraiture *et al*. (2008) state furthermore that the most important biofuel crops are sugar cane and maize, of which sugar is a cash crop and maize is mainly used to feed animals for milk and meat production, which could lead to a conflict between ''cars and carnivores'', not affecting local food production. However, competition between meat and fuel is unlikely since only the kernels are used to produce ethanol while the whole plant can be used as feed for animals. The same occurs with vegetable oil production from soybean where the oil can be used for biodiesel and the rest can be fed to animals. In this case biodiesel can almost be considered as a by-product, because of the high demand for animal feed derived from soybean. As the production of biofuels in the USA is based on maize and soybean, it may be complementary to meat production.

In this context, Wassenaar and Kay (2008) state that the production of biofuels is just one of the many claims to natural resources made by agriculture, and, therefore, biofuel production should not be addressed in isolation of other agricultural activities. After all, farmers switch per cropping season from one crop to another based on expected economic returns, rather than on the expected end use of their produce. It is for this reason that Fresco (2006) claims that the production of biofuels can diversify agricultural activities, and, if proper policies are implemented, food and feed farming can potentially solve both local food shortages and increase the incomes of the world's poorest people, without devastating effects on the environment. With regard to the use of freshwater resources for biofuel production, this statement is probably true for most parts of the world, as shown here. However, since feedstock production comes predominantly from large monocultures, it is likely that valuable ecosystems like wetlands and rainforests will be cleared to make space for sugar cane and oil palm plantations, resulting in losses of natural biodiversity. Rather than the impact on water resources, which will be important locally, the impact of biofuel production on land resources and biodiversity is probably more of a reason for concern.

CONCLUSIONS

Current water withdrawals for the production of biofuels are minor compared to the total water withdrawn for other agricultural uses. The estimates as presented in this paper are of the same order of magnitude as the estimates done by De Fraiture *et al*. (2007). However, due to the absence of reliable statistics on irrigated area and yield per crop, uncertainties remain about the reliability of the absolute figures underlying these global assessments.

Looking at the projected production values for biofuels over the next 10 years, it is not expected that increased biofuel production will have a major impact on water resource availability in the near future. Even if the production

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of ethanol in 2017 increases by 65% and is produced from the same feedstocks as today, under the same agricultural practices, the global water withdrawal for biofuels would not exceed 2% of the total amount of water withdrawn for agriculture.

Latin America and sub-Saharan Africa still have abundant land and water potential to be developed for both rainfed and irrigated sugar cane production which could give an economic impulse to the agricultural sector in these regions. However, feedstock production comes predominantly from large commercial monocultures for which valuable ecosystems may need to be cleared and from which only a marginal part of the rural population may benefit. In both regions, these are considerations that are probably more important than the impact of biofuel production on water resources.

There is reason for concern in India, China, Thailand and South Africa. Here high economic growth is resulting in an increased demand for both food and energy and consequently an increased demand and competition for fresh water. For India and China the water withdrawn for biofuel production will remain modest compared to the total amount of water used for irrigation, but in both countries there are places where every drop of extra water withdrawn counts and adds to already severe water stress. Thailand and South Africa are countries under water stress for which a significant increase in bio-ethanol production is projected. If the projected amount of bio-ethanol in these countries is produced from irrigated sugar cane, it will contribute notably to existing stress levels.

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