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REVIEW

Present and future water requirements for feeding humanity

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Abstract The Comprehensive Assessment of Water Management in Agriculture recommended that future food production should be concentrated on existing agricultural land in order to avoid further loss of ecosystem functions from terrestrial lands. This paper is a green-blue water analysis of water constraints and opportunities for global food production on *current croplands* (including permanent pasture). It assesses, for the target year 2050, (1) how far improved land and water management would go towards achieving global food security, (2) the water deficits that would remain in water scarce regions aiming at food self-sufficiency, (3) how those water deficits may be met by food imports, (4) the cropland expansion required in low income countries without the needed purchasing power for such imports, and (5) the proportion of that expansion pressure which will remain unresolved due to potential lack of accessible land. The water surplus remaining on current cropland is compared with water requirements for biofuel production as a competing activity.

Keywords Global future food production · Green-blue water analysis · Water deficits · Food import · Cropland expansion · Unresolved ultimate water deficit

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> The last 50 years have also witnessed unprecedented changes in ecosystems, with many negative consequences. The Millennium Ecosystem Assessment pointed out that growth in agriculture has been responsible for much of this change…..Our message: better water management can mitigate many of the negative consequences.
>
> Summary for Decision makers, Comprehensive Assessment of Water Management in Agriculture (CA 2007)

Introduction

The concern with and targets for measures against malnourishment and hunger are of very long origin. Before Ban Ki-moon, Secretary-General of United Nations, we have heard his earlier colleagues Waldheim, Boutros Gali and Kofi Annan all call for decisive efforts towards global food security. Still today, the number of malnourished in the world stays stubbornly close to one billion people, despite the latest commitment of the world community through the UN Millennium Development Goals (MDG) to half hunger by 2015, only 6 years from now. Ban Ki-moon, Secretary-General of the United Nations, in his recent article "The new face of hunger", stressed that an urgent response is needed, that global food stocks are at historic lows, and that agricultural production must be boosted (Ki-moon 2008). Nothing less than a new green revolution is required to lift people out of hunger in Sub-Saharan Africa, the most vulnerable region in the world in terms of food and poverty.

In the 2008-report on MDG-achievements, rising food prices and increasing concerns over water scarcity put in doubt the ability to achieve future global food security under a business as usual approach: rural populations are suffering from the cumulative neglect over decades of the agricultural sector (UN 2008). This crisis has highlighted the importance of giving greater attention to developing the agricultural sector and addressing the needs of rural populations. Moreover, the report stresses the urgency of ensuring that the present course of action be accelerated and expanded. It also stresses the fact that international trade negotiations are years behind schedule and the need for corrective action.

Despite rapid urbanization, 70% of the world's poor live in rural areas, which makes local agriculture central to increased production and socio-economic development. Earlier analyses indicated a certain level of congruence between poverty, under-nutrition and hydro-climatic water scarcity (Rockström et al 2007). Although there is not a universal one-to-one relation, the conclusion, supported by the Comprehensive Assessment on Water Management in Agriculture (CA 2007), is that the world's savannah zones (the semi-arid tropical regions, generally defined as drylands) constitute a global hot-spot in terms of great water challenges, high levels of poverty and malnourishment. These facts call for special attention to be paid to the agricultural production potential of the semiarid tropics. Also, the increasing river depletion in irrigated regions has contributed to focusing new attention on rainfed agriculture and the potential of micro-agricultural water management technologies (AWM) for food security (Falkenmark and Molden 2008, CA 2007; Merrey and Sally 2008).

When discussing rainfed agriculture, the analysis of freshwater availability is based on the green and blue water framework developed by Falkenmark and Rockström (2004). Blue water resources are defined as the generated runoff stored in aquifers, lakes, wetlands and reservoirs. Blue water flows are composed of the flux of surface and sub-surface runoff. Green water resources are defined as the infiltrated rainfall in the unsaturated soil layer forming soil moisture that is on its way to evaporate back to the atmosphere. Green water flow is the vapour flux from the terrestrial ecosystems to the atmosphere, which is composed of non-productive green water flow (evaporation) and productive green water flow (plant transpiration), generally combined into the evapotranspiration, ET, i.e., total green water flow.

Ban Ki-moon, in the above article, suggested that there is no reason that Africa cannot experience a "green revolution" (Ki-moon 2008). The green revolution that lifted large parts of S Asia from an agricultural crisis in the 1960s and 1970s was, however, based on irrigation, i.e. using blue water and fossil fuel driven pumps. In view of the serious environmental impacts of past irrigation, Conway (1997) stressed that a new green revolution has to be green-green, as the boosted agricultural production has to be environmentally sound. The authors of this paper—later supported by the conclusions of the CA—provided evidence to show that not even this is enough. A new food revolution, essentially doubling food productivity on agricultural land in sub-Saharan Africa and parts of South and South-east Asia, will have to incorporate a green–green–green revolution, based on managing green water in rainfed agriculture (Rockström et al 2003; Merrey and Sally 2008)—in other words a triply green revolution: green for production increase, green for being green water based, and green in the sense of environmentally sound. The second water related "green" originates from evidence that the conventional strategy to provide water for food production through irrigation will be far from enough; even an optimistic analysis of the potential contribution from blue water to attain the MDGs, indicates that it will contribute less than 20% of the required additional amount (Rockström et al. 2007).

Although the real problem for food, water, energy and environmental security is how to best manage these resources in combination and how to coordinate their development policies, the food security challenge of the coming decades—the ultimate constraint of future food production—has to be analysed. It is also necessary to provide evidence for strategic opportunities to obtain sustainable water resources for agricultural development. This is critical, given the fact that food production is one of the world's largest freshwater consuming sectors, and that the process of growing biomass consumes huge volumes of water (an adequate diet consumes in the order of 1,000–1,300 m^3/capita/year). In order to get an idea of the future food production problem in terms of scale, regional differences, and need for expanded food trade, it is necessary to analyse the food situation also through a freshwater lens. Therefore, in this paper we analyse water constraints and opportunities for global food production and nutritional value, both fundamental components of food security. We also take into account affordability by linking country income and the emerging need for intercountry exchange through expanded trade in food.

In view of the unprecedented changes in ecosystems caused by past growth in agriculture (CA 2007) and the CA recommendation to concentrate improved water management on existing agricultural land to reduce loss of ecosystem functions and services from terrestrial lands, this paper analyses the potential of improved agricultural production on *current croplands* (including permanent pasture). It assesses, for the target year 2050, how far improved land and water management on current cropland would go towards global food security, the possible water deficiencies that would remain in water scarce regions aiming at food self-sufficiency, how to meet that water deficit, and the water surplus beyond food water requirements in regions that are better water-endowed, as well as the cropland expansion required in regions where purchasing power is too low to cover the deficit by food imports. We also estimate the proportion of this expansion pressure that will remain unresolved due to absence of accessible virgin land.

The paper thereby presents an integrated socio-ecological analysis of the global food challenge which links the potential to increase food production, focusing on land and water resources through a green-blue analysis, with the social demand for food and the economic capacity for its purchase.

Methods

The data underlying this study were generated by the well-established LPJml dynamic global vegetation and water balance model (Gerten et al. 2004), incorporating both population growth and climate change under the economy-oriented SRES A2 emission scenario, involving slow fertility decline. In that scenario, the increasing water shortage over the next few decades is due primarily to increasing population (Rockström et al. 2008).

All calculations in this analysis address the situation projected for 2050 as compared to the situation in 2000, and were made per country for two population scenarios: in addition to the rapid growth scenario just mentioned, taken from the SRES A2 model of the IPCC 4th Assessment (IPCC 2007), calculations are also made for the slower growth scenario of the UN medium population prediction.

To estimate water needs for food per country, dietary water requirements per capita were multiplied by the future population in each country. To produce a food supply, corresponding to the average supply in developing countries as foreseen by FAO (2003) for 2030, would require an average production of 3,000 kcal/capita/day. Assuming that 20% of this is animal protein, an estimated 1,300 m^3/capita/year of freshwater would be needed (Rockström et al. 2007); however, with future improvements in water productivity (WP) this food water requirement could probably be reduced to approximately 1,000 m^3/capita/year in 2050, thus resulting in lower future water requirements for food production. In the discussion, we will return to the possibilities of also reducing the amount of food wasted “from field to fork”.

Data on total water availability per country on current croplands (green and blue water) was estimated by Rockström et al. (2008). By comparing water availability with water requirements for food before and after improvements in WP, each country either had a deficit or a surplus of water. All country specific deficits were summed to form a global total. The surpluses were treated analogously.

The water deficits could be met in different ways, first of all by expanding irrigation. The combination of serious streamflow depletion in irrigated regions and environmental flow requirements (Smakhtin et al. 2004) will, however, limit such expansion possibilities. We simply assumed that an additional 15% of the available blue water resource could be used (consumptive water use as evapotranspiration, ET) on irrigated lands in all countries with an irrigation expansion potential according to the FAO (FAOSTAT 2003). However, irrigation expansion was not allowed to exceed the level where a country is classified as chronically water short (<1,000 m^3/year of available blue water per capita). Nor was it allowed to exceed the irrigation potential converted to water units, assuming an average of 10,000 m^3 consumptive water use per hectare of irrigation area expansion. This resulted in an estimation of additional blue water availability for irrigation, which was allocated towards either reducing the deficit or added to the surplus, depending on the situation in each country.

Water consumed on (non-permanent) grazing lands contributes to the amount of water available to meet food water requirements. Two thirds of the total water requirement for food production is used for animal based food items, and around 25% of this comes from grazing globally (Rockström et al. 2007). Based on these figures, an estimate of the water consumed on grazing lands in each country for grazing meat production was made, which in turn was compared with the total green and blue water availability on grazing lands (Rockström et al. 2008), and the lowest value of the two was selected to represent consumptive water use on grazing land for food production. It was assumed that only 50% of the total water availability on permanent grazing lands could be used sustainably in order to safeguard the generation of other ecosystem services as well. The consumptive water use on grazing lands was subsequently allocated towards reducing the deficit or increasing the surplus of water, depending on the local situation.

Summarising the impacts of improvements in WP, irrigation expansion and water contributions from grazing lands, generates either a deficit or a surplus of water in relation to food water requirements in each country. This deficit or surplus can be met either by trade or by horizontal expansion, i.e., by converting other terrestrial ecosystems to crop land. To analyse the potential for trade, each country was classified according to their gross national income (GNI) in 2005 (World Bank 2005) in three different classes: low, middle and high income countries (World Bank 2008). Based on cereal import and GNI data, it was assumed that there is a positive relationship between import potential and GNI (FAOStat 2003; World Bank statistics 2005). Thereafter, countries were categorized according to their hydro-climatic (deficit or surplus water resources) and socio-economic (trade or expansion) factors.

It was assumed that the low income countries facing difficulties in meeting water requirements, will not be able to rely on trade in the future, and will thus have to expand agriculture horizontally. The expansion is expected to be done in two steps: first into present grazing lands, by allocating the total remaining unallocated green and blue water availability on grazing lands towards food production (the share that has not already been appropriated for grazing in meat production), and then secondly by expanding into other lands. This latter expansion was translated into land area requirements based on figures from Rockström et al. (2008). An estimate was also made of potential water saving by reducing losses in the food chain, from field to consumption.

Results

Water deficit countries

In a first step, the available green water resource on current cropland area is estimated at country level. We focus the analysis on the potential to meet food water requirements on current crop land in order to assess the possibility of avoiding cropland expansion at the expense of further ecosystem degradation. When the available green water resource is too small to meet national food water requirements, blue water may be added to the cropland by irrigation. As pointed out in Methods, we have limited the additional irrigation potential to a 15% increase. This is in order to account for the limited opportunities to increase blue water withdrawals from rivers, lakes and aquifers, without unacceptable decline of aquatic ecosystem functions and services.

Conventionally, water scarcity analyses are based on comparing only blue water availability with future water for food demands. These analyses generally result in very high estimates of the proportion of people and number of countries subject to water scarcity, as they assume that blue water is the only freshwater resource contributing to food production. The reality is very different, with an estimated 5,000 km^3/year of consumptive water use originating from green water in rainfed agriculture, and "only" approximately 2,000 km^3/year from blue water consumption in irrigated agriculture. These "blue" water analyses obviously exaggerate the global water problem, and at the same time under-estimates the potential to produce food in regions that are blue water scarce (but that may be rich in green water resources—such as in savannah regions of the world). As pointed out earlier by the authors (Falkenmark and Rockström 2004), such analyses are therefore flawed, and require a broadened green-blue analysis. Such an analysis is shown in Fig. 1, which illustrates in green the number of countries in 2050 facing freshwater (green + blue) surpluses (>1,300 m^3/cap/year in water for food availability over current agricultural land) and in orange/red countries facing freshwater deficits (<1,300 m^3/cap/year). This map reveals a broad zone of water deficit countries all the way from Morocco in the west to India in the east (countries which are normally also assessed as water stressed in blue-water analyses). Countries close to deficit are highlighted in yellow where there is a green plus blue availability of only 1,700 m^3/cap/year—a limit frequently used in blue water scarcity analyses (cf. correlation between food trade and blue water shortage, Yang et al. 2003). In this perspective China and a few sub-Saharan countries also emerge as approaching a critical situation.

Country-level water deficiencies and surpluses

The cumulative country-based food water requirements by 2050 amounts to approximately 14,200 km^3/year for the

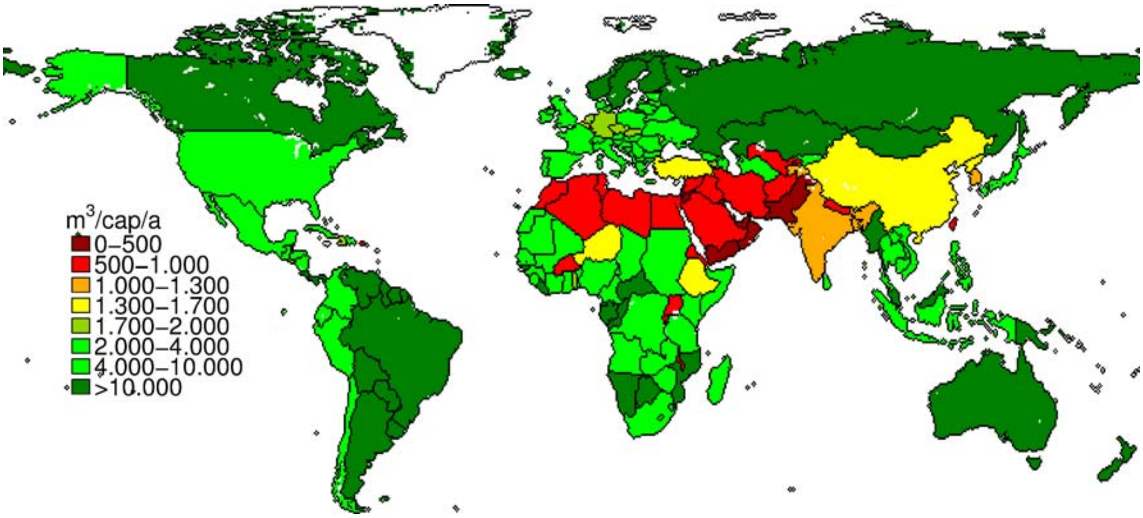

Fig. 1 Countries colour coded according to water availability for food self-sufficiency. Those with <1,300 m^3/capita/year are in deficit. See text for details. From Rockström et al. 2008

SRES-A2 population projection and to 11,900 km^3/year for the UN medium projection. The total green water availability by 2050 on current croplands was estimated at 6,260 km^3/year, to which was added a blue water irrigation contribution of an estimated 1,820 km^3/year. This gives a total water availability (blue plus green) of 8,085 km^3/year. The difference between the cumulative requirements of 14,200 or 11,900 km^3/year and the total green plus blue availability of 8,085 km^3/year results in a global water deficit by 2050 of 6,130 or 3,800 km^3/year.

Summing up water availability, country by country, gives higher values as surpluses and deficits between countries no longer compensate each other. This results in a country-based water deficit in 2050 of 7,500 or 5,510 km^3/year and a surplus of 1,380 or 1,710 km^3/year.

This analysis shows that concerns for future food production constraints are clearly well founded even when taking a broader green-blue water approach, although such analysis reduces the water deficit as compared to a "blue water only" analysis. The next question is: what options are there to meet these massive water deficits? We will start by analysing the potential contributions from

- water productivity improvements
- irrigation expansion
- contribution from grazing on permanent pasture lands

Water productivity improvements and irrigation expansion

Improving water productivity for food production greatly reduces the deficit by about 2,000–3,000 km^3/year, while increasing the surplus in water rich countries by about 450–550 km^3/year, depending on population scenario (Table 1). Irrigation expansion further reduces the deficit by 400–600 km^3/year. In relation to improvements in water productivity, the figure is small, which is due to the fact that in many countries experiencing a total water deficit for the production of food, the blue water availability is already limiting and irrigation expansion is thus not feasible. Irrigation expansion in surplus countries added some 1,100–1,300 km^3/year. This vast amount includes an exceptionally large increase in a few countries with large rivers, such as Brazil.

Grazing fodder contribution

All animal protein does not originate from cattle fed on feed from croplands. A portion of animal protein is produced from grazed fodder. We estimate that water consumed on *non-permanent* grazing lands for meat production may result in a reduction of 700–900 km^3/year in water requirements for food production in water deficit countries, while increasing the surplus of water availability in water rich countries by 400–500 km^3/year. These are rather conservative estimates on the contribution of water from grazing lands, due to the uncertainty related to upholding the generation of ecosystem services and maintaining resilience in these ecosystems. However, the overall improvement in water productivity indirectly assumes that livestock water productivity of grazing meat production is also improved.

Food trade to compensate the remaining net water deficit

A remaining net deficit of some 2,200–3,300 km^3/year (Table 1) in water short countries could theoretically be met by food imports from water rich countries, since the surplus in the latter category of 3,400–4,000 km^3/year exceeds the deficit. However, the question is will poor countries be able to afford the required imports of food? The classification of countries into those with low, medium and high incomes reveals that more than half of the deficit is located in low income countries, while the majority of the surplus is found in medium income countries (Table 2). Even when assuming the less pessimistic UN medium projection of population growth and a feasible improvement of water productivity, there will remain a water deficit of some 2,200 km^3/year in water short countries, making them dependent on either food import or, alternatively, on cropland expansion. With the assumption made regarding purchasing power—that

Table 1 Country based estimates of water deficits and surpluses for food production in 2050

Population assumption	A2		UN	
	Deficit (km^3 year^{-1})	Surplus (km^3 year^{-1})	Deficit (km^3 year^{-1})	Surplus (km^3 year^{-1})
Deficit/surplus, no actions taken	7,510	1,380	5,511	1,708
WP improvements	−2,820	460	−2,220	520
Irrigation expansion	−550	1,130	−430	1,300
Grazing fodder	−880	480	−710	440
Net deficit/surplus (round numbers)	3,260	3,450	2,150	3,970

SRES A2 and UN medium population scenarios

Table 2 Country level water deficits and surpluses for food self-sufficiency (km^3/year) and populations involved in millions of people (Mp): SRES A2 and UN medium population scenarios

Income (2005)	Deficiency	Surplus
Low	1,730/1,400 km^3/year	310/410 km^3/year
Cropland expansion	4,190/3,790 Mp	
Food export		470/480 Mp
Medium	1,200/490 km^3/year	2,240/2,680 km^3/year
Food import	3,110/2,120 Mp	
Food export		1,960/1,610 Mp
High	330/260 km^3/year	890/880 km^3/year
Food import	540/520 Mp	
Food export		670/630 Mp

countries with an GNI below 1,000 US$/capita/year will not have enough purchasing power to import their food—it will be difficult for these countries to avoid a cropland expansion into other land of the order of some 300 Mha. This expansion can be compared with earlier assessments. The senior authors in a study of 92 developing countries arrived at the somewhat larger figure of 450 Mha, part of which would be covered if food import continued at the present level (Rockström et al. 2007).

In 2050 it is estimated that of the order of one third of the world's population will live in each of the three regions: those that export, those that import and those that have to expand their croplands. This means that an estimated 3.8–4.2 billion people will live in regions which cannot produce enough food on current croplands, and where the import potential may be limited by weak national level wealth (as seen from the income situation 2005).

Globally, the water deficit countries are distributed mainly in the tropical zone, while the countries experiencing a surplus of water are located in the temperate region (Fig. 2). Countries which might be forced to expand agriculture horizontally at the expense of other ecosystems are found in Africa and S Asia, predominantly in the Savannah zone.

Cropland expansion—the remaining option

Parts of the horizontal expansion in the low income countries with a water deficit could be met by utilizing the total water availability on current grazing lands specifically for food production. Countries with large grazing lands will be able to contribute considerable amounts of water if used for crop production. The contributions are especially large (beyond 20 km^3/year) in Brazil, Philippines, Zaire, US and Mexico. This entails converting grazing lands to crop land, assuming a higher level of food output per unit land (e.g., converting grazing lands generating in the order of 1–2 tons of grazing dry matter per hectare, to grain yields in the order of 2–3 tons per ha). This will result in higher water consumption per unit area though, potentially reducing blue water generation and water availability for other ecological functions and biodiversity.

We have also tried to analyse how much of the cropland expansion that will remain unresolved (Table 3). The remaining deficit, after considering the option of converting grazing lands to crop land, is 1,000–1,300 km^3/year. This corresponds to 200–300 Mha of virgin lands that would have to be converted to agricultural lands in order to meet food water requirements.

This expansion can be compared with earlier assessments. In a recent analysis of 92 developing countries, we arrived at the somewhat larger estimate of expansion requirement of 450 Mha, out of which a part would be covered if food imports were continued at the present level (Rockström et al 2007).

The general picture which emerges is that most of the developing countries in Africa and Asia will be dependent

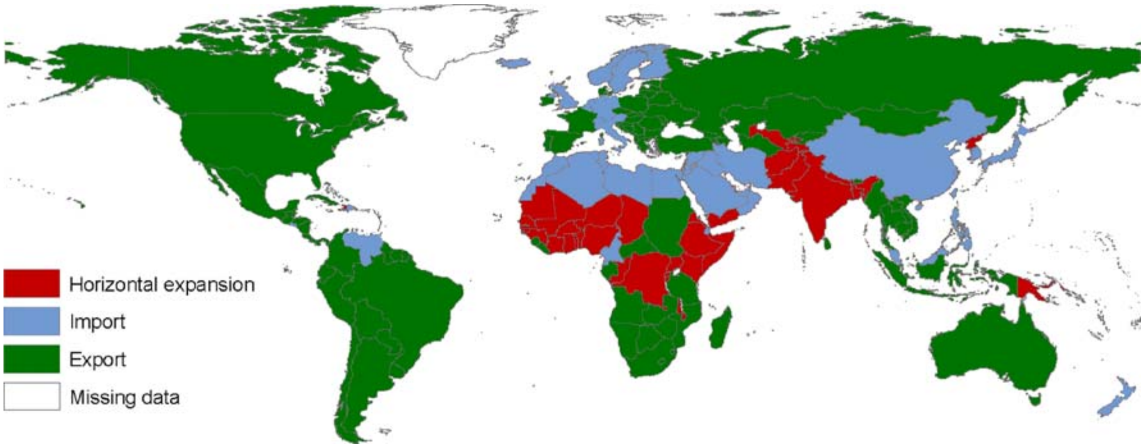

Fig. 2 Food importing and exporting countries from a water availability perspective in 2050, including low-income, water short countries which most likely will have to rely on horizontal expansion of agriculture

Table 3 Cropland expansion required by 2050

	UN medium scenario		A2 population scenario	
	Mha	km^3/year	Mha	km^3/year
Grazing land	80	398	85	424
Other land	201	1,002	261	1,304

Water deficit (km^3/year) to be covered by cropland expansion into grazing land and other unspecified land (million hectares) to meet food water requirements

on either large-scale food imports, or in case of the lowest income category of these countries, on horizontal expansion of their croplands. In Africa, the latter group includes Benin, Burkina Faso, Burundi, Eritrea, Ethiopia, Gambia, Malawi, Niger, Nigeria, Rwanda, Togo and Uganda; and in Asia, Afghanistan, Bangladesh, India, Nepal, N Korea, Pakistan and Yemen. No attention however, has been paid to whether horizontal cropland expansion beyond pastures will be possible.

Grazing land can only cover less than one third of the needed cropland expansion, most of which will have to incorporate other land, i.e. grasslands and forests. Most of this expansion will take place in Africa, where there is large potential but a set of Asian countries also belong to this group. The largest expansion needs may be expected in India (72 Mha), Pakistan (27 Mha) and Bangladesh (23 Mha). In this region, the potential, however, is very low—most arable land is already in use. This leads to the conclusion that these countries are approaching the end of the road unless income growth in the meantime allows them to import the food required. They could therefore constitute a fourth category of country with a population of altogether 2.4 billion, unable to secure food supply at the required calorie level. Also Ethiopia, Eritrea and Somalia belong to this fourth particularly vulnerable group where income rise will be especially critical for hunger eradication. The “overpopulation” of these countries in the sense that the population cannot be fed if other lands are not accessible for cropland expansion amounts to some 650 millions.

Discussion

In this paper we analyse the world food challenge from a freshwater perspective. We combine this with an additional boundary condition for agricultural production in the future, namely to secure ecological resilience in agricultural landscapes, particularly biological diversity, by emphasizing the need to avoid continued expansion of cropland beyond grazing land.

As a first step, the analysis shows that the world will not, by 2050, have exceeded its carrying capacity—despite escalated food demand—as seen from a water-constrained food production perspective. The net water deficit is estimated to be 2,200 km^3/year in countries facing water scarcity (3,270 in the A2 population scenario), but there will be a net surplus of an estimated 3,960 km^3/year (3,440 in the A2 population scenario) to cover it in water rich countries.

Water deficit implications

The group of water deficit countries that will be relying on import to feed their populations by 2050 encompasses the chronically water short countries in N Africa, W, S and E Asia. Also belonging to this group are industrial countries such as Japan and a set of European countries that are overpopulated in relation to their cropland areas, including Italy and Germany. Food exporting countries will be located in N America, C America, the former Soviet region, southern African countries and some European countries with plenty of cropland area and surplus freshwater resources.

The result of this analysis is sometimes counter-intuitive. Namibia and Botswana, both extremely water short countries, have water availability—mainly as green water—beyond what will be needed to be food-self sufficient. This is the result of taking a green-blue water perspective and indicates the potential of increasing food production even further by adopting green water management practices, such as conservation tillage, mulch farming, water harvesting and soil and water conservation practices. As shown from agricultural trials, yield levels of maize can in fact be more than doubled in Botswana, by adopting such practices (SIWI 2001).

Uncertainties

However, there are many uncertainties both within the analysis as such and the social-ecological driving forces not considered here. The study is model-based, using best available data and is, as a consequence, no better than the limitations following from, on the one hand, data uncertainties and, on the other, the model itself. It has therefore to be seen as mainly indicative only. One consequence is the uncertainty of blue water availability in arid climate zones where the model’s neglect of natural blue water evaporation tends to exaggerate this availability (Gerten et al. 2004).

In reality, also many other constraints exist. We address water impacts induced by climate change using one scenario. There are though huge uncertainties regarding water resource implications of climate change over the coming 50 years. Furthermore, we do not address, in an explicit way, constraints related to climate variability on the farmers’ fields, i.e., droughts, dry spells, and floods. In the same way, we do not in any explicit way address constraints related to soils. However, we do address both these factors (water variability, soil and crop related constraints) through our water productivity analysis (see below).

Importantly, the analysis is static with regards to assumptions on economic growth in the future. Obviously, it is a pessimistic assumption that the countries today classified as unable to substitute own food production with large-scale imports of food, will remain in this predicament also in 2050. A weakness in this analysis is that we assume the current level of income distribution among the countries in the world to remain the same as today in our 2050 scenario. Obviously, the countries that we estimate will be forced to expand agricultural land (they have neither the water resources on current agricultural land, nor the purchasing power to substitute production for imports) may follow a better economic growth trajectory in the future than in the past. The dynamics of regional economic growth may change the wealth distribution in the world, and thereby shift the flows of food on the Planet. However, food trade today accounts for only a small part of food provision (only 15% of staple food consumption is traded and this is imported to a significant degree by rich, arid countries). Most developing countries continue to prioritize food self-sufficiency in their domestic policies, which may suggest a continued focus on national food production potentials.

Future diets are another source of uncertainty. We have here assumed that the current "standard" diet of 20% animal based foods and 80% plant based foods will prevail. We have furthermore not considered the impacts of reducing the often large post-harvest losses of food. There is no doubt that a substitution of grain-fed meat towards more plant-based diets could save significant volumes of freshwater in the future. A final major uncertainty relates to demographics. We have assumed here two scenarios, including the UN medium scenario assuming a stabilization of the world population at approximately nine billion people. If this turns out to be too high, the dire water future we paint here would be exaggerated. On the other hand, nothing today points at a population trajectory lower than this. Finally, we would like to point at the possibilities of technological innovations, both in terms of genetic modifications of crops that may improve water productivity, and breakthroughs in the use of unconventional water sources (such as desalinized water). Today, desalinization is far too expensive for staple food crops. However, in a future with a breakthrough in, for example, solar energy technology, this may change.

Water productivity improvements

The only way to significantly improve water productivity in agricultural systems is to also raise agricultural productivity. We have in this paper applied a very optimistic analysis of the opportunities to improve water productivity by raising yield levels in farming systems based on past and recent evidence. The assumptions on water productivity improvements originate from assessments of agricultural productivity enhancements from implementing practices that improve soil, crop and water management. These include conservation tillage, soil fertility management, soil and water conservation, water harvesting, integrated pest management and crop improvements.

As shown by Rockström et al. (2003), there is a particularly great opportunity to improve water productivity at the low-yield range due to the current large losses on non-productive green water flows. Improving yield levels from the current 1–2 t/ha for staple food crops (such as maize, millet, and sorghum) to 3–4 t/ha would shift water productivity from 2,000–3,000 m^3/t for the low yielding farming system to 1,000–2,000 m^3/t for the higher yielding system. Once yields exceed approximately 4 t/ha, the incremental increase in water requirement for every incremental increase in yield returns to the (normally assumed) linear relation between water and food (constant WP of approximately 1,000 m^3/t).

This highlights a very important point—that the triply green revolution benefits from the fact that the largest untapped potential to save water in food production is in the lowest yielding savannah regions of the world and these are also are the regions where growth in food production is fastest due to population growth and where a green revolution is therefore most needed. Estimates of the potential to raise agricultural productivity through improvements in soil, crop, and fertility management, suggest that even a doubling of food crop yields is achievable in currently low-productive agricultural regions with current know-how (Rockström et al 2003; CA 2007). Serious policy impediments, including traditional Western professional training, have however delayed a scale up in the use of these technologies (Merrey and Sally 2008).

When it comes to the relative effectiveness of water productivity improvement as compared to irrigation expansion within the constraints applied in this study, improved water productivity is the most effective measure in most parts of the water deficit regions in Africa and Asia. It is basically in a limited set of C African countries that irrigation might be more worthwhile than water productivity improvements.

Food supply assumption

It can of course be argued that the required food supply assumption of 3,000 kcal/capita/day, out of which 20% is animal protein, is an exaggeration of food needs. This is partly a question of what dietary energy supply level may be considered adequate when averaging over the whole population, including the poor and undernourished. It has been shown (SEI 2005) that presently some 3,000 kcal/capita/day is adequate for most countries to satisfy basic food needs for all. Partly it is a matter of the considerable losses "from field to fork" (SIWI 2008) which determines food production having to be much higher than the actual food intake. Our assumption is in fair agreement with assumptions by others as shown by CA (2007) where the overview presented (Table 3.1 p 96f) shows that both CA, IWMI and FAO projected food supply to be around 3,000 kcal/capita/day.

This assumption can be compared to the per capita averages estimated from Smil (2000), and based on FAO statistics (Lundqvist et al. 2007) of the edible food harvested, post harvest losses and food waste, and net food available for consumption in the mid 1990s: in this publication the actual food supply was 2,900 kcal/capita/day (our assumption 3,000), 17% animal protein (assumed here to be 20% by 2050) and a possible water productivity improvement of 24% (assumed here to be 23% by 2050). The water required for animal protein production was, however, estimated at only 1.7 m^3/1,000 kcal (our estimate 4 m^3/1,000 kcal due to the very high water requirements of cattle producing meat and dairy, cf. Lundqvist et al. 2007).

That study also assessed the food wasted "from field to fork" at 30% of the food produced, arriving at a food intake of only 2,000 kcal/capita/day in the 1990s. If a 50% reduction of that food wastage were possible by 2050, as assumed by Lundqvist et al. (2007), this would imply that a food supply of about 2,500 kcal per capita per day would be acceptable in 2050. Assuming also WP improvement, the food water requirements would decrease from 1,000 to 840 m^3 per capita per year which means 160 m^3 per capita per year saved, or globally for a world population of nine billion around 1,440 km^3/year.

Conclusions

The major contribution of this paper is to show, from a water perspective, on the one hand, the new opportunities that exist in the short term to meet rapidly growing food demands sustainably and on the other, the difficult decisions that may face humanity on the long term (by 2050) when food demand will outpace water availability in many regions of the world, despite an optimistic analysis of access to freshwater and efficient use of this water.

Overview

Opportunities arise from the adoption of an integrated green-blue water approach, which instantly increases the window of freshwater availability to meet future food needs with more than 60% (often more than 80% in drier regions). Despite this broadened framework, social drivers rapidly push water demands towards a new breaking point, where even a green-blue water approach combined with optimistic outlooks on water productivity, are insufficient.

Our analysis shows the following ways in which the massive food water deficit of 6,800 km^3/year (7,510 km^3/year minus the 710 km^3/year contributed as green water from pasture, see Table 1), that threatens to develop by 2050 may be reduced

	Deficit reduction (km^3/year)
Limited population growth (UN rather than A2 scenario)	2,000
Water productivity improvement	2,220
Irrigation expansion	430
Food import from water surplus countries	750
Cropland expansion into non-permanent pastures	130
Unresolved ultimate water deficit	1,270

The study clearly shows that—although food security depends on a wide set of different factors and resources, the physically limited and most basic of these resources—the freshwater that makes the photosynthesis-based biomass production possible—will introduce a fundamental constraint in some regions of the world. Although the study is indicative only in view of the many uncertainties including lack of proper income projections for 2050, it gives an idea of the countries in the most precarious situation regarding food security. In these countries it will be particularly important to direct economic development towards raising enough purchasing power to be able to feed the projected population two generations from now. Efforts to reduce food waste would evidently improve the situation—how far is difficult to judge since only global averages are available.

Sobering up the ethanol debate

Table 1 gives indications of the remaining water surpluses and the potential for water available for biofuel production on croplands. For slow fertility decrease scenario (case A2), only 170 km^3/year of water remains for bioethanol production; for the UN medium case some 1,800 km^3/year. Even the latter is less than half the water required for energy crop production in 2050, assuming only 25 ton energy crop per GJ bioenergy feedstock (Lundqvist et al. 2007, Table 7 and 8). These simple facts make it imperative to link more closely the projections for food production with cropland-based bioethanol production, so that any opportunities identified remain realistic.

Final remarks

What this study has shown is that food security will meet considerable problems in view of both a continuing population growth and the foreseen climate change during the next four decades. It presents a perspective from which not only blue water in rivers and aquifers are referred to as the water resource, but also the naturally infiltrated soil moisture/green water supporting both rainfed and irrigated agriculture. In the first part of the twenty-first century efforts with "triply green" agriculture in savannah regions may be successful but in the course of the next few decades, population growth will overtake this technology and considerable water deficits will develop in large areas of the developing world. The analysis in this paper shows the implications of eradicating world hunger, in line with the philosophy of the first of the Millennium Development Goals and, by indicating the scale of future food trade required for global food security, raises concerns for current delays in international trade negotiations.

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