CHAPTER 1

Food security in water-short countries – Coping with carrying capacity overshoot

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ABSTRACT: Given that water is the core resource for plant production, the study analyses the carrying capacity overshoot threatening a large part of the planet by 2050 AD, in view of current dietary tendencies towards 3,000 kcal/day per person with 20% animal-based food. It shows the enormous unbalance caused by population growth and the ambitions of the Millennium Development Goals (MDGs) of hunger alleviation if environmental sustainability should be met. The world is moving towards a future where indeed 2/3 of the world population because of water constraints will be depending on the remaining 1/3 for supplying them with part of their food needs, so that they can feed their population at the assumed dietary level. This would necessitate more than doubling of today's trade-based virtual water transfer to compensate for foreseeable food water deficits. But food security in some poor countries would still remain problematic due to lack of purchasing power to import. Half of these countries might solve their future food supply by aiming at lower animal based food. Others will have to seek support from other nations, in terms of emergency aid to avoid horizontal expansion, or continued undernourishment. It will thus be essential for the world to steer away from current dietary tendencies in terms of water-consuming animal-based components. Much can be gained already by moving from today's 20% to the 5% considered satisfactory for human health.

Keywords: water-based carrying capacity, virtual water transfer, food water deficits, purchasing power, dietary tendencies, water productivity

1 FOOD SECURITY CHALLENGE

Humanity faces an unprecedented challenge of meeting rapidly growing food demands on a planet with shrinking per capita availability of water and land resources that can be sustainably used, and where water constraints will in many parts of the world rise due to anthropogenic climate change. Molden (2007) estimated that water for food production will have to increase from current 7,000 km^3/yr to some 9,000–11,000 by 2050. This increase involves a challenge of a scale nothing less than a new green revolution.

1.1 *Sequence of approaches*

The issue of water and food supply for a growing humanity was raised by Swedish scientists already at the UN Population Conference 1974 in Bucharest, based on an informal document (Falkenmark & Lindh, 1974). While the UN Food Conference in Rome also in 1974 addressed the foreseeable need to expand irrigation, the UN Water Conference in Mar del Plata in 1977 broadened the perspective of blue water, i.e. liquid water in rivers and aquifers; the UN information material included the publication "Water for a starving world" (Falkenmark & Lindh 1976).

Attention to the link between food and water shortages continued through the following decades. In the 1980s, the severe droughts in the 1970s and 1980s drew attention to the links between water shortage and hunger (Figure 1). It was observed that around 20 African countries hit by the hunger catastrophe caused by the 1984–85 drought (Figure 1, Map 1) in fact shared a number of underlying water shortage characteristics (Falkenmark & Rockström, 1993):

– Water-related soil problems: short growing season (Figure 1, Map 2), infiltration/land degradation problems (Figure 1, Map 4).
– Water availability problems: low runoff generation (Figure 1, Map 5), large rain variability (Figure 1, Map 3).

In the 1990s, international attention was directed to the possibility to import food to countries too water-short to base food supply on irrigation; the word *virtual water* was introduced to denote the hidden water transferred by export (Allan, 1993; 1994). Numerous studies have later quantified the amounts of virtual water transferred between regions in this way (e.g. Chapagain *et al.*, 2006; Yang *et al.*, 2006; Hoekstra & Hung, 2005; Hoekstra, 2003). Attention was also drawn to the fact that most water involved in food production was in fact not blue (liquid), but green, i.e. infiltrated rain, accessible as soil moisture in the root zone (Falkenmark, 1995; Rockström, 1997). Later, climate change added a new perspective, raising an interest in the *agricultural green water potential*, and the *carrying capacity of the planet* if adhering to the Millennium Development Goals (MDGs) of hunger alleviation while securing environmental sustainability (Rockström *et al.*, 2005). Attention was also drawn to the *consumptive use* component of irrigation. It was observed that with increased irrigation development total withdrawals in many basins exceeded renewable supply, and with intensified reuse the depleted fraction of the utilizable flow would approach 100% in many basins. The concept *basin closure* was introduced to describe the path and stage of river depletion (e.g., Keller *et al.*, 1998; Molden *et al.*, 2005).

To eradicate hunger in line with the MDGs is an increasing challenge. In the first decade of the 2000s, a central question that caught increasing attention was which parts of the world will have enough water to be food self-sufficient, and which parts will not. More and more attention went into projections of future water requirements for feeding the world by 2050 when population would be expected to stabilise (Rockström *et al.*, 2007; Molden, 2007; Rockström *et al.*, 2009; Falkenmark *et al.*, 2009). Already today total consumptive water use for food production has been estimated at around 7,000 km^3/yr (Molden, 2007). From present world population of about 6,900 million in year 2010, projections point at an expected increase of about 32% to 9,100 million by 2050 (UN medium projection), with almost the entire increase located to the less and least developed countries (UN, 2010, 2008 revision). The absolute number of undernourished have oscillated around 850 million since the beginning of the 1970s. After the food and economic crisis 2007–2009 the estimates for year 2008 showed for the first time a total above 900 million, and estimates for 2009 indicated a continued rapid increase to more than 1,000 million (1,020 million) (FAO, 2009a).

In short, these 40 years of global food security analysis basically lead up to the conclusion that particular attention has to be paid to the implications of continued population growth in water short countries when combined with the MDGs, in particular in terms of hunger alleviation.

1.2 *This study*

Large differences in terms of hydroclimatic preconditions for an expanded crop production between different geographic regions have raised further questions (Rockström *et al.*, 2010). What will be the relation between the water-rich regions with potential to produce a surplus of food to be exported to water-short regions with continuing population increase, unable to produce the amount needed to feed their populations on an acceptable nutritional level? What parts of the food-deficient regions will be able to cover food deficits by imports? What parts will have to depend on food aid? How large virtual water flows will this transfer of food from well-supplied to deficit regions imply? What options are available to countries unable to pay for imports?

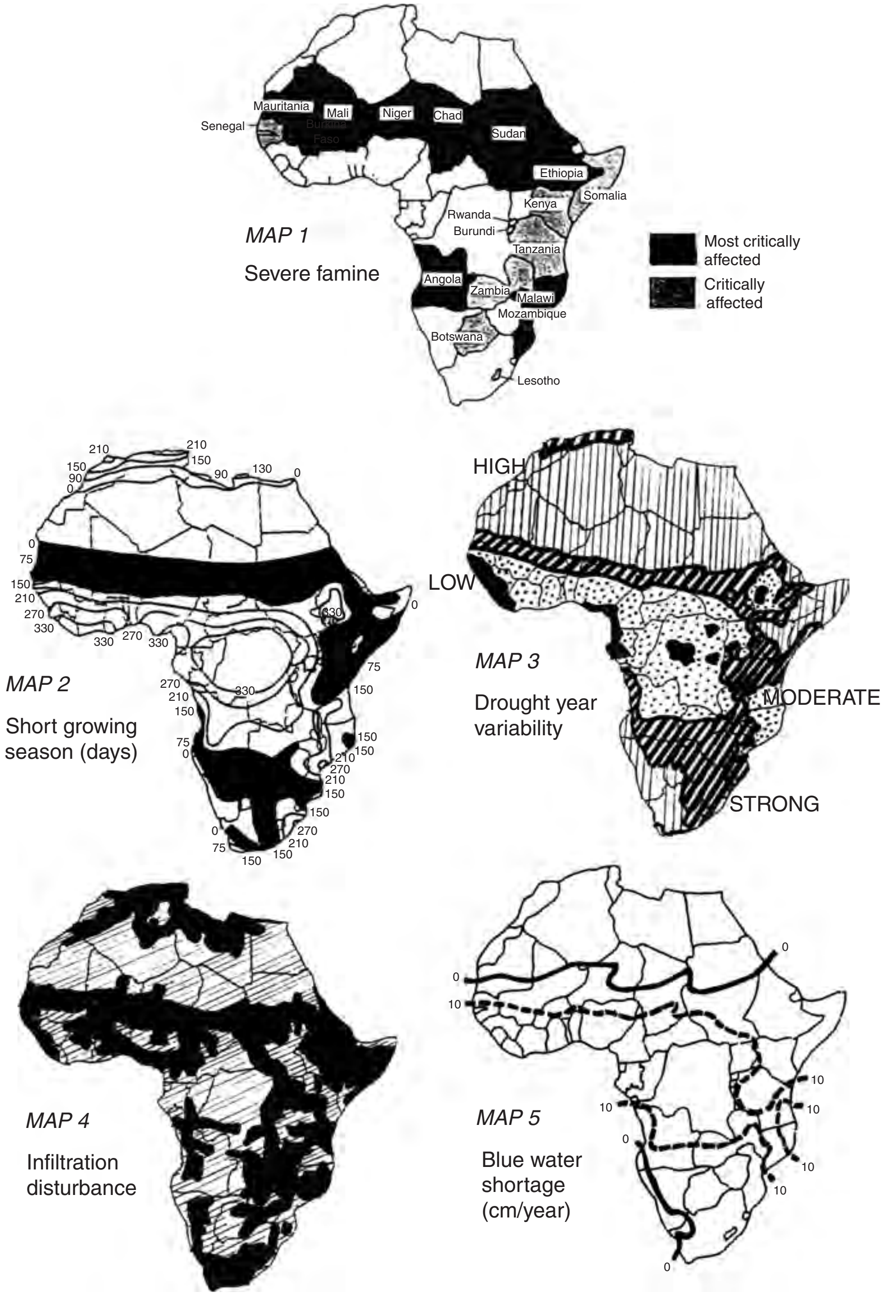

Figure 1. Links between sub-Saharan proneness to famine and complex water scarcity.
Source: Falkenmark & Rockström (2004).
Legend: Map 1: Severe famine (1984–85 drought); Map 2 and 4: Green water shortage (2: growing season below 150 days; 4: infiltration disturbance/land degradation); Map 3: High green and blue water variability (striped: two severe drought years in a row 5–7 times in 50-years period); Map 5: Blue water shortage (rainfall below 100 mm/yr).

Our study is a further advancement of a recent model-based studies by Rockström *et al*. (2009, 2010) which was a country-based analysis based on the LPJmL dynamic global vegetation and water balance model (Sitch *et al*., 2003; Gerten *et al*., 2004; Rost *et al*., 2008). It was a back-casting study analysing the options for resilient and sustainable water resource supply for food production by 2050, assuming the UN medium population projection and no cropland expansion in line with the MDG goal on environmental sustainability. The present study goes on from there by further analysing the water short country dilemmas and realistic options to close the water deficit gap. Particular attention is paid to the importance of respectively economic development, water related carrying capacity overshoot, emerging water deficits, and the importance of the animal protein component for the consumptive use water requirements.

2 METHOD

2.1 *Scenario*

The underlying study (Rockström *et al*., 2010) assumed that by 2050 climate change has proceeded according to the SRES A2 scenario, and the population grown to 9,100 million [UN Medium Population] by 2050); that the MDGs have been reached, i.e. hunger alleviation achieved in all countries; and that environmental sustainability has been respected (in the sense both of avoiding further expansion of croplands to protect terrestrial ecosystems and of respecting the needs for environmental flow to protect aquatic ecosystems).

2.2 *Per capita food supply level*

For the first estimates a general per capita food supply demand of 3,000 kcal/day per person was used. This level was earlier used by Falkenmark & Rockström (2004) and is projected by FAO to be reached in developing countries by 2030 (Alexandratos *et al*., 2006). An average of 20% of the per capita food energy supply is assumed to originate from animal foods to ensure sufficient protein content. This is in line with the present rising global average of 17% and the fact that many less developed countries with rapid economic development have already reached above 20% (e.g. China 22%) (Lannerstad, 2009; FAOSTAT, 2009) (see Figure 2).

In the following analysis of countries with water-related carrying capacity overshoot we use three food supply level combinations. First is the general level specified above. For the second level the animal foods content was lowered to a minimum acceptable level of 5% considered to be enough from a health perspective (Smil, 2000), but the 3,000 kcal/day per person level retained since the food actually eaten is much lower due to food losses from the market to the dinner table. The third level corresponds to what is considered the necessary food intake level of 2,200 kcal/day per person (Smil, 2000), assuming a *loss free* food consumption system.

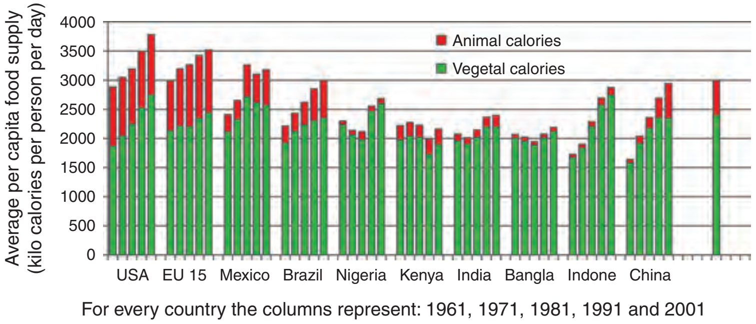

Figure 2. Average per capita food supply per day for 1961–2001 separated into vegetal and animal calories. Last pillar to the right shows assumed food supply of 3,000 kcal/day per person, 20% animal calories.
Source: Adapted from Lannerstad (2009); data source: FAOSTAT.

2.3 *Agricultural water requirements*

Based on previous global assessments under current water productivity levels (Falkenmark & Rockström, 2004; Rockström *et al*., 1999) we assume that the evapotranspiration on average required to produce the equivalent of 1,000 kcal of vegetal foods is 0.5 m^3, while 4 m^3 per 1,000 kcal is required for animal products. More water is required to produce animal foods, because only part of the vegetal energy consumed by animals is transformed into e.g. meat, milk, or eggs. The values used here are equal to or lower compared with earlier estimates (Pimentel *et al*., 1997; Cai & Rosegrant, 2003; Chapagain & Hoekstra, 2003). The result is annual per capita agricultural water requirements of 1,300 m^3 for our food supply level of 3,000 kcal/day per person with 20% originating from animal foods.

2.4 *Agricultural water availability*

Blue and green water availability on current managed agricultural lands (i.e. croplands and permanent pasture) was estimated on a country-by-country basis to distinguish countries with surplus of water, able to export food to countries with a water deficit, unable to support their populations (Rockström *et al*., 2010).

2.5 *Water surplus/deficit analysis*

When cropland green water availability was compared with food water requirements on a country by country basis, a gross water deficit of some 4,500 km^3/yr was identified. Table 1 shows the implications of plausible water productivity improvement, and irrigation expansion and their effects in bringing down the gross water deficit to a *net agricultural deficit* of 2,150 km^3/yr in water short countries (23% of the water requirements). In water rich countries, on the other hand, the surplus above what will be needed for food self-sufficient production amounts to almost the double.

A conclusion from these results is evidently that there will be enough water in the world to support a population of 9,100 million by 2050. The future problem will therefore not be to produce enough food, but how to allocate it to the people in dry and overpopulated countries, heading for carrying capacity overshoot.

2.6 *Food trade analysis*

In our study, the implications of food trade have been analysed for two different projections in terms of economic trends in South and East Asia and Africa, respectively. Case A assumes no economic development in low income countries, case B assumes an economic development in line with a recent World Bank categorisation (Income group: Economies are divided according to 2008 GNI per capita, calculated using the World Bank Atlas method. The groups are: low income, US$ 975 or less; lower middle income, US$ 976–3,855; upper middle income, US$ 3,856–11,905; and high income, US$ 11,906 or more) (WB, 2009), and allowed a new differentiation of developing countries as compared to the earlier one in Rockström *et al*. (2010).

Table 1. Country-based estimates of agricultural water deficits and surpluses for food production in 2050 (UN Medium Population scenario).

	Deficit (km^3/yr)	Surplus (km^3/yr)
Water deficit/surplus	4,471	2,052
Water productivity improvements	−1,973	532
Irrigation expansion	−348	1,379
Net deficit/surplus	**2,150**	**3,963**

Source: Rockström *et al*. (2010).

The study has furthermore analysed the water/food security pathway by looking closer at the country based food security gap, and the relative size of the main options by which the food water deficit may be met.

3 ECONOMICALLY BASED COUNTRY COMPARISONS

Table 1 clarifies that water productivity improvement and irrigation expansion more than halved the original water deficit based on current water productivity. What remains is a net water deficit gap of 2,150 km^3/yr in vulnerable water short countries. Possible options to meet this food water gap include virtual water transfers through trade from water surplus to water deficit nations. Countries without purchasing power will be left to national solutions like horizontal expansions, risking unsustainable land use, or to aim for less water intensive diets by lowering the per capita food supply calorie level and/or the animal food ratio. In some cases food aid, another virtual water transfer solution, might be the only solution.

3.1 *Importance of economic development*

Since food trade expects people to pay for the transferred food, the 2009 study (case A) suggested that only populations in medium and high income countries would be able to do so (see Table 2). Case A is based on the assumption that the relative economic situation in the water short countries would not change very much in the next 40 years from the situation around 2000 AD. This would imply that only some 750 km^3/yr of the deficit could be covered by virtual water transfer through trade, leaving the food supply of the 3,800 million poor and water short to so-called *other solutions*, in terms of conversion of pasture to croplands, cropland expansion, reduced diet expectations, or aid, case A in Figures 3 and 4.

However, considering past economic trends in many developing countries with rapid economic growth during the last decades, e.g. India, it may be reasonable to assume that the relative purchasing power of some of the low income countries will in fact increase till 2050 (case B). Assessments of economic growth in different regions (Sulser *et al.*, 2009) clarifies the need to look separately at South Asia with an assessed economic development 2000–2050 of 5.1% per year as opposed to sub-Saharan Africa with only 2.8% per year. Within regions there may be individual countries with a stronger development as opposed to countries with a lower growth. The World Bank categorisation (WB 2009) reflects this economic development perspective by sorting all countries into four income categories: *high*, *medium high*, *medium low*, and *low*, thus moving some of the

Table 2. Comparison of country level net annual water deficits and surpluses and population for Case A and B, summarized for different country income categories.

Case A				Case B			
Country income groups (WB, 2005)	Net deficit 2,150	Net surplus 3,963	km^3/yr	Country income groups (WB, 2009)	Net deficit 2,150	Net surplus 3,963	km^3/yr
Low	1,404	407	km^3/yr	Low	602	381	km^3/yr
	3,785	477	million		1,492	464	million
Medium	487	2,680	km^3/yr	Medium Low	1,242	646	km^3/yr
	2,115	1,614	million		4,246	659	million
				Medium High	46	2,044	km^3/yr
					160	950	million
High	259	876	km^3/yr	High	260	892	km^3/yr
	522	631	million		524	649	million

countries from *low* in case A to *medium low*. This would radically change the purchasing power assumptions in some water short countries with large populations, turning the global food security outlook to the classification as shown in Figure 4, case B. In case B the 3,800 million people *deficit other solutions* sector from case A have been rearranged so that 2,300 million have been moved up

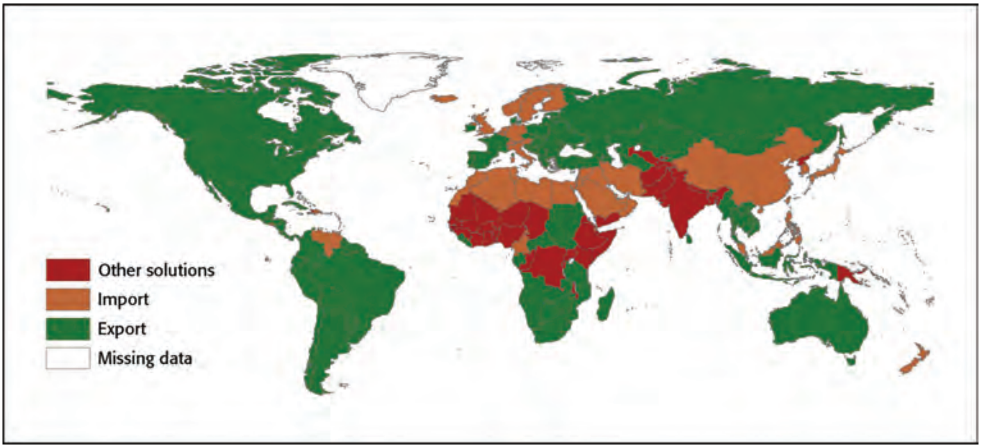

Figure 3. Food importing and exporting countries from a water availability perspective in 2050, including low-income, water short countries which may have to rely on other solutions.
Source: Falkenmark *et al*. (2009).

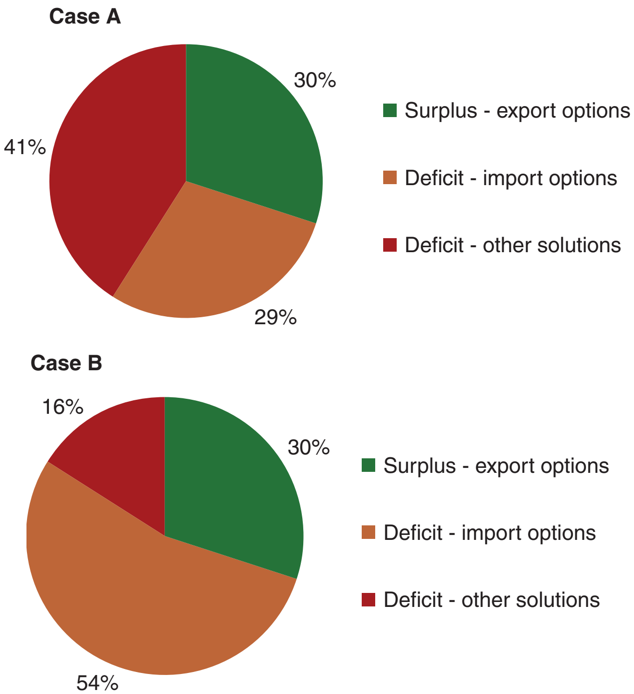

Figure 4. Comparison of population vulnerability by 2050 in water short countries for Cases A and B. The circles show percent of world population living in countries with export options, import options, and having to rely on *other solutions* to meet food demands under different assumptions on rate of economic development and purchasing strength on the global food market. Case A: no advancement of Low Income countries; Case B: WB 2009 land categorisation.

to the category *medium low*, expected to manage a certain food import. This leaves only a future population of about 1,500 million that because of limited purchasing power on the international market will have to find other solutions but trade to secure a sufficient food supply.

Comparing now the two cases A and B, we may conclude that global water security is growing into a massive trade challenge. Water constraints will increasingly be shaping the basic food supply predicament. Two thirds of the world population will be living in countries where tomorrow, i.e. 2050, today's China/Brazil/Mexico diet (cf. Figure 2) cannot be provided from current croplands, even after agricultural modernisation in terms of plausible increase of agricultural water use efficiency and irrigation increase. If today's economic situation in water short countries would remain (case A), only half of that population might be able to compensate their food security deficit by import from the surplus countries (altogether corresponding to 2,600 million and some 750 km^3/yr). If however more South and East Asian countries are categorised to belong to the *medium low* income category of countries (case B), altogether almost 5,000 million people might be able to import to compensate their food water deficit. This would more than double the virtual water flow by trade, increasing it from today's 1,300 km^3/yr by another 1,550 km^3/yr.

Altogether around 35% of the remaining food water deficit in case A and 70% in case B would therefore depend on a well functioning system of food trade.

3.2 *Poor water short country options*

For case A, Rockström *et al*. (2010) analysed how much food the 3,800 million in the 39 poor water short countries by 2050 might in fact be able to produce within their agricultural water availability constraints. The first option is to intensify agricultural production by expanding cropland onto present pasture. By doing this, a water deficit of about 400 km^3/yr in countries with 390 million people can be met. For the remaining 20 countries the second option was to reduce the dietary expectations. It was suggested that for 600 million, the problem was not really serious but an issue of reducing the animal protein part of the diet. About 1,900 million would be able to produce on average 2,500 kcal/day per person with a 10% fraction derived from animal foods. The remaining 1,300 million in the most precarious situation would only be able to produce some 2,000 kcal/day per person with reduced or no contribution from animal foods and therefore remain dependent on aid to avoid broad undernutrition.

As a result of the assumed increased purchasing power in case B, only 29 countries with a total population of 1,500 million would still continue to belong to the water deficit *low income* group. After expansion of croplands onto existing pasture lands, as in case A, about 230 km^3/yr can be gained. For the case B only 17 countries with a total population of 1,200 million would still belong to the water deficit *low income* country group. Nine of these countries would be able to manage their national food supply just by heading for an Indonesian average food supply of about 3,000 kcal/day per person and 5% animal foods (see Table 3 and Figure 2). Altogether 8 countries with a population of almost 500 million would remain with less than the 560 m^3/yr per person needed to sustain such a diet, and would remain dependent on horizontal expansion into other terrestrial biomes wherever possible, or indeed food aid. Bangladesh, the least water short of these countries, lacks only about 2% of the water required to feed its population, while Togo, the most water short in this group, lacks 55% of the water required. The remaining water deficit for these 8 countries amounts to 49 km^3/yr.

Summarising the results so far, our comparison has shown that:

- Only 30% of the 2050-population would be living in countries with enough water for food self-sufficiency on the assumed dietary level (current Brazil-China diet level).
- 2,600 (case A) or 4,900 million (case B) depending on to the economic development in Asia would be able to cover their food water deficit by import from water rich regions of the world.
- 3,800 (case A) or 1,500 million (case B) would be left as poor and water short. In case B 12 countries in this group can meet their water deficit by converting pasture to croplands, 9 countries would be able to manage on a 5% animal protein level, leaving the remaining 8 countries dependent on aid or horizontal expansion to cover their deficit. Four of these countries might

be able to produce the food needed provided that there are no food losses (the *loss free* option) which is however mainly to be seen as a theoretical possibility only, i.e. an untapped option to be explored in the future.

4 FOOD SECURITY PATHWAY

The above analysis has revealed three key obstacles relevant for global food security by 2050:

a) Assumed preferences for animal-based food (20%) will not be achievable and are exaggerated as compared to health motivated amounts (5%) (countries 1–9 in Table 3).
b) Food losses, demanding an overproduction of food items to eliminate undernourishment of parts of the population in a country (illustrated by countries 10–13).
c) Overpopulation in comparison with the water-controlled carrying capacity of the countries (countries 14–17).

In this section we will carry the analysis further and compare, on the one hand, the different components by which the revealed global food deficit gap may be closed. On the other hand, we will look at the main factors that contribute to accelerating that gap.

Table 3. Food supply options to meet national net water deficits for the 17 different countries with net supply below 1,000 m^3/yr per person under Case B. Left part of the table shows country wise data; in right part striped areas indicate country dietary options.

	Total Food Supply Level		kcal/day per person		3,000	3,000	2,200		
	Proportion Animal Foods		%		20	5	5		
		Total population 2050	Per capita Net Deficit 2050	Per capita Net Supply 2050	Full Food Supply	Full Energy Supply Minimum Animal	Supply only intake "Loss Free"	Other Solutions	Diet and Other Solutions Water Volumes
	Country	million	m^3/yr per person		1,000	560	410	<410	km^3/yr
1	Congo, Dem. Rep.	187	20	980					Less animal foods 321
2	Afghanistan	79	90	910					
3	Ethiopia	183	210	790					
4	Nepal	52	240	760					
5	Uganda	93	250	750					
6	Eritrea	11	250	750					
7	Korea, Dem. Rep.	25	270	730					
8	Gambia, The	4	290	710					
9	Burkina Faso	38	370	630					
10	Bangladesh	254	450	550					Horizontal expansion or Aid 49
11	Rwanda	23	580	420					
12	Niger	53	590	410					
13	Yemen, Rep.	58	590	410					
14	Malawi	32	630	370					
15	Benin	23	690	310					
16	Burundi	28	730	270					
17	Togo	14	740	260					
Total		1,156							370

4.1 *Closing the water deficit gap in water short countries*

Figure 5 shows the relative role of different ways to close the country-based water deficit gap in the country-level food security pathway curve. The gap may principally be closed *from above* with increased efficiency or lowered food demand thus reducing the consumptive water use requirements through water productivity improvement, diet expectation adaptation, and if possible food loss reductions, or *from below* by additional water through irrigation, virtual water from surplus regions (trade and aid), making use of non-productive evaporation on current pasture lands, or horizontal cropland expansion.

4.1.1 *Water productivity increase*

The importance of water productivity increase was demonstrated in the study by Rockström *et al.* (2010) on which this study builds. As already stressed, the gross water deficit of 4,500 km^3/yr with present water productivity can with improvements be brought down by almost half to 2,500 km^3/yr (Table 1). This implies that the current water requirement of 1,300 m^3/yr per capita can be reduced to 1,000 m^3/yr per capita by 2050 by implementing practices that improve soil, crop and water management (conservation tillage, soil fertility management, soil and water conservation, water harvesting, integrated pest management and crop improvements) (Rockström *et al.*, 2007). There is a particularly great opportunity to improve water productivity at the low-yield range (Rockström, 2003; Rockström *et al.*, 2007; Molden *et al.*, 2010). This highlights a very important point –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 the regions where escalation in food requirements is fastest due to population growth and where a green revolution is therefore most needed.

4.1.2 *Irrigation*

In the past much attention has been paid to irrigation as the primary way to find relief from agricultural water shortage. In recent years, it has however become evident that the irrigation expansion during the green revolution had very serious environmental impacts. One serious effect is the flow depletion in numerous rivers in a broad land ribbon from North-East China in the east, to South-West USA in the west (Smakhtin *et al.*, 2004). Some well known and alarming examples

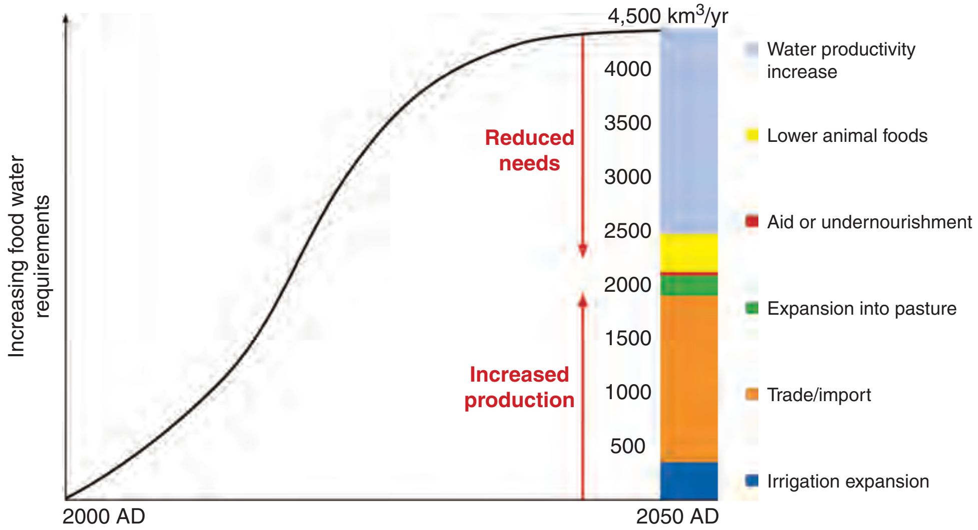

Figure 5. Global food security pathway outlook for agricultural water deficit countries, and options for closing the food water deficit gap.

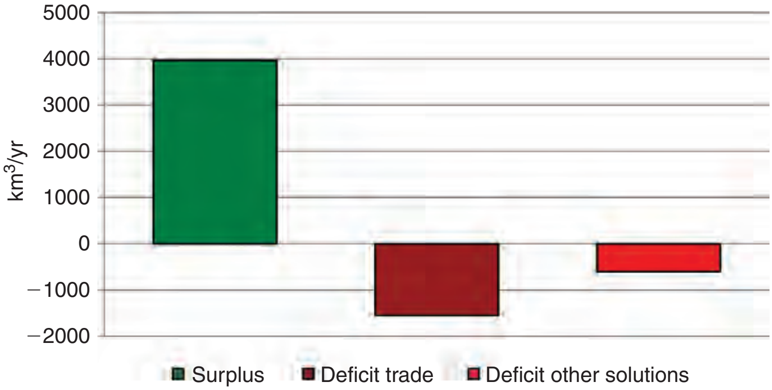

Figure 6. Case B country group categories, showing agricultural water surplus and deficits by 2050. Depending on level of economic development and expected purchasing power the deficit can be met by either trade or other solutions.

of rivers that are running more or less dry during parts of the year are the Nile, the Colorado River, the Yellow River, and tributaries Amu Darya and Syr Darya to the depleted Aral Sea, but there are numerous others (Lannerstad, 2002; Falkenmark & Lannerstad, 2005). A river basin with no usable outflow has been described as evolving from an *open* to a *closed* state (Seckler, 1992; 1996). The term *basin closure* is now widely used in the sense of very little additional water being left in the river for further human uses and in terms of enough water being left for the aquatic ecosystems (generally 30% of the total available blue water resources) (Falkenmark & Molden, 2008; Molle *et al*., 2010).

Groundwater overexploitation is a parallel and increasing dilemma. Rosegrant *et al*. (2002) estimated total groundwater use to more than 800 km^3 in 1995, out of which as much as 200 km^3, was assessed as overdraft of non-recharged groundwater (Postel, 1999). Well documented areas with long-term groundwater depletion are the North China Plain (Kendy *et al*., 2003), the USA Great Plains with the Ogallala aquifer (Postel, 1999) and several states in India, e.g. Gujarat (Moench *et al*., 2003).

As a consequence of these effects of consumptive water use and overexploitation, the contribution that irrigation may offer to close the water deficit gap is surprisingly limited in relation to improvements in water productivity, although the assessments vary between different authors. Given the assumptions in this study, Rockström *et al*. (2010) assessed that irrigation might in the deficit areas contribute in the order of 350 km^3/yr, i.e. of the order of only 8% of the total deficit, an assessment in agreement with what de Fraiture & Wichelns (2010) estimated as an optimistic, but plausible scenario.

4.1.3 *Virtual water transfers through trade, land grabbing and aid*

The relation between water surplus and water deficits for case B is shown in Figure 6. Virtual water flows through trade would meet a deficit of 1,550 km^3/yr, leaving 600 km^3/yr to be met by other solutions. Our estimated trade increase will thus stand for 35% of the total deficit. Already today some water scarce regions are heavily dependant on imports. One example is Northern Africa where about 50% of the cereal food consumption is based on imports (FAOSTAT, 2009). Compared to present virtual water flows through trade of agricultural products (some 1,300–1,600 km^3/yr) (Chapagain *et al*., 2006; UNESCO, 2009), our figure indicates more than a doubling of the global needs.

Besides the necessary purchasing power of the importing countries, three requirements will have to be met. The basic prerequisite is that surplus countries manage to produce enough food for export. A large production increase poses a true challenge even if agricultural water availability does not

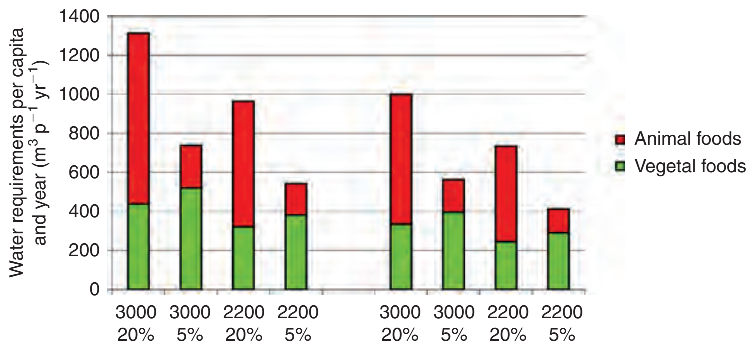

Figure 7. Different ways of bringing down food water demand from a calorie and animal *vs*. vegetal foods water perspective. [See text].
Four columns to the left: present water productivity of 1,300 m^3/yr per person.
Four columns to the right: expected water productivity by 2050 of 1,000 m^3/yr per person.

involve any constraint. The second necessity is an upscaling of the global food transport infrastructure to handle doubled trade volumes. This will mean investments in land and sea transports as well as other infrastructure like harbours and food storage. The third and most difficult factor is a well functioning global food market. During the food crisis 2007–2008 many countries implemented export restrictions, e.g. 40–44% in East Asia and South Asia (FAO, 2009b). As pointed out by von Braun & Meinzen-Dick (2009), the food crisis and the volatility in food markets have undermined the trust in trade and is a main cause behind foreign investment in agricultural land, often called *land grabbing*. This trend of state controlled virtual water flow started already some years ago. China began to lease land for food production in Cuba and Mexico 10 years ago and continues to search for new opportunities to feed its large population (*ibid*.).

4.1.4 *Cropping pasture*

Some of the water deficits can be met by expanding croplands on to permanent pasture lands. In the underlying green blue water flow analysis (Rockström *et al*., 2010) it was assumed that livestock production only utilises 50% of the vapour flow from permanent pasture lands. When converting these areas to croplands, it is assumed that the remaining 50%, presently sustaining other terrestrial ecosystems can be appropriated by crops and meet a deficit of about 230 km^3/yr. Out of the total remaining 600 km^3/yr water deficits, only 370 km^3/yr would be left to be met by other measures. Although cropping pasture will have negative effects on non-agricultural ecosystems co-existing on pasture lands, it maximises production on already domesticated lands and minimises the expansion and environmental degradation into areas that remain largely untransformed for human agricultural needs.

4.1.5 *Less water intensive diets*

As described above, three average per capita food supply combinations are used in this chapter. For those countries that because of water deficits cannot produce a full diet our study point at the possibility to reduce the animal foods content. The Indonesian case in Figure 2 offers an alternative of almost 3,000 kcal/day per person and only a minor fraction of animal foods.

Figure 7 visualises the water requirement gains for the different food supply levels (vegetal *vs*. animal foods fractions), and food loss reduction for the two alternative water productivity levels. By reducing the animal content from 20 to 5% for the 3,000 kcal level a reduction of almost 45% in agricultural water requirements can be achieved. This shows the crucial multiplying impact of increased animal foods contents in our diets.

The importance of the animal foods factor calls for further research. In line with Rockström *et al*. (1999) it has been assumed that 0.5 m^3 of evapotranspiration is required to produce 1,000 kcal

Table 4. Relative scale of potential water deficit alleviation components (km^3/yr).

Food security pathway components	km^3/yr
Water productivity increase	1,973
Trade across national borders	1,548
Irrigation expansion	348
Lower animal foods proportion	321
Conversion of pasture to croplands	232
Aid or undernourishment	49
Total water deficit alleviated	**4,471**

of vegetal foods and 4 m^3 per 1,000 kcal of animal foods, i.e. that animal foods production needs eight times as much water per produced calorie. This relation however depends on the kind of and combination of animal production systems (grazing, cultivated fodder, and cultivated feed), and the feed conversion efficiency for different species and the breeds of these species (e.g. traditional or modern) (Lannerstad, 2009).

4.1.6 *Horizontal expansion of croplands and pasture into other terrestrial biomes*

Even if non desirable from the perspective of environmental sustainability, horizontal expansion into forests and other terrestrial ecosystems is nevertheless an option to enlarge agricultural lands and increase food production. In a number of countries, hosting altogether some 600 million people (Bangladesh, Burundi, Nigeria, Rwanda, Togo), the populations are however so large that more terrestrial land (forestry and other land uses) than what is even totally available would be required to meet dietary water needs. That is to say that even if the whole terrestrial area of the country could be converted to croplands, this would still not meet the total water requirement to feed the whole population. Horizontal expansion is therefore not considered in our analysis.

4.1.7 *Scale overview*

The above overview of the relative contributions to closing the food deficit gap in water short countries identified in Section 3 gives the relations shown in Table 4. The single most effective contribution is water productivity increase, which reduces the food water deficit gap of the water short countries by 44%. Food trade would be able to contribute to meeting 35% of the water deficit. Irrigation expansion is much less effective as seen on the global scale. Lowering the animal food component of the current dietary tendencies and cropping of pasture land can also only add minor volumes. In our analysis, these options are considered only for the residual low income countries without trade opportunities. The aid needed to support the eight countries not able to meet their food needs even after water productivity increase, crop cultivation on pasture lands, and lowered animal-based food expectations amounts to no more than 50 km^3/yr, or only about 1% of the total global food water deficit.

4.2 *Major factors driving the water deficit gap*

Turning now to the main factors that tend to accelerate the global food deficit gap of water short countries by 2050 AD, we will highlight three main aspects:

- Urbanisation, economic development and diet composition.
- Losses along the food chain.
- Population growth.

4.2.1 *Economic development, urbanisation and diet composition*

By 2050 about 70% of the estimated world population of 9,100 million will live in urban areas (UN, 2010). Higher disposable incomes will drive a trend towards higher per capita calorie levels and a global convergence of diets, in terms of e.g. the increasing poultry consumption and similar eating habits, with fast and convenience food. The urban dwellers lose the traditional connection to the local agricultural production, and gradually become consumers on the urban, and thus also on the international, market (Lannerstad, 2009). Relatively monotonous diets based on indigenous staple grains or starchy roots, locally grown vegetables, other vegetables and fruits, and limited foods of animal origin will be replaced by more varied diets that include more pre-processed food, more foods of animal origin, more added sugar and fat, and often more alcohol (Steinfeld *et al*., 2006). Consumption of meat and milk and dairy products in all developing countries (not considering China and Brazil) may double till 2050.

The importance of economic development for changed average supply patterns is clearly visible in Figure 2. USA and the EU15 represent economically strong regions with a high urban majority. Mexico, Brazil and China show a rapid increase in both average calorie levels and fast rise in the proportion of animal foods. India, also a BRIC country like Brazil and China, has a more recent economic boom and probably has only begun the climb up the food and animal foods ladder.

4.2.2 *Food losses –an unnecessary agricultural consumptive water use*

Producing more food than actually eaten is equivalent to a consumptive use of large amounts of a scarce water resource. Today, food losses are in fact considerable (Lundqvist *et al*., 2008). According to Smil (2000), in 1990 vegetarian produce equivalent to some 4,600 kcal/day per person were being harvested while the amount food consumed was estimated to only 2,000 kcal/day per person. Out of the difference about 1,400 kcal/day per person, or 30%, represents post harvest and food losses. If all losses along the food chain, from farm level to the actual intake could be eliminated, future average per capita food consumption could be optimally brought down to the average food energy requirement of 2,200 kcal/day per person (Smil, 2000), the estimated minimum need for a healthy life. Since food losses are practically very difficult to avoid, a future food supply level of only 2,200 kcal/day per person is not really a very realistic option (Lannerstad, 2009). Figure 7 however clearly visualises the importance of food loss reduction. When the average food supply level at 3,000 kcal/day per person is reduced to only 2,200 kcal/day per person, but with the same animal food proportion the water requirements can be reduced by about 27%. Although loss reduction is desirable, Figure 7 visualises that reduction of animal foods is much more important. With both loss and animal foods reduction the per capita water requirements can be reduced by about 60% down to 400 m^3/yr per person.

The considerable benefits that could be reaped if food losses could be minimised however suggests that efforts to reduce losses must be immediately started in both developed and developing countries. The character of losses differs considerably between developing and developed countries. With modern harvest, transport and storage techniques, it would be a realistic option for many developing countries to dramatically reduce losses on the way from field to the market. In the USA and Europe the major losses and waste take place in the latter half of the food supply chain (Lundqvist *et al*., 2008). However, if the countries rapidly becoming middle-class societies like China, Brazil and Mexico follow the same market and consumption system path as already is established in the developed world they risk replacing one wasteful food system with another (Lannerstad, 2009).

4.2.3 *Population growth*

As shown by Falkenmark *et al*. (2009), the difference in food water requirement by 2050 between the two population projections SRES A2 (10,900 million) and the UN medium population (9,100 million) contributes an amount to the water deficit gap of water short countries equal to low water productivity, i.e. of the order of 2,000 km^3/yr. Finding acceptable ways to keep population growth under control –especially in water short countries– would therefore be an effective way of limiting the food water deficit gap that will have to be met.

Basically, population growth is however not an issue of fertility decline only but also of momentum and rising live length. The age structure of a population is important. Even after the total fertility rate reaches replacement level in a country (two children per woman), the population continues to grow as the decline in mortality increases the number of old people in the population.

Although population growth rate has in fact slowed from some 2% per year in the 1960s to only 1.2% per year at present, the absolute growth and therefore the pressures on the carrying capacity of the Planet continues to be very high (Sachs, 2008). The continued population increase in countries, scarce in water and other natural resource, like India, is therefore a crucial factor when analysing the future global food challenge. The importance of population growth control is illustrated when comparing population development projections for China and India. With its one-child policy since 1979 China will reach its peak population of around 1,460 million about 2030 which will decrease to 1,420 million by 2050. India will on the other hand be the most populous country by 2050 with a population of about 1,610 million after an increase of more than 400 million (UN, 2010).

5 SUMMARY AND DISCUSSION

The above analysis has thrown interesting light on global food security by mid 21st century, given climate change, population growth and current dietary tendencies. It is however essential to stress that the study has been based on climatic averages only, with no attention to increasing variability. This variability will probably increase food supply challenges even further. Neither is any attention paid to soil fertility or to biomass production activities competing for production on agricultural land, such as fibre and biofuel production.

5.1 *Carrying capacity overshoot*

Although the international debate on global food security during the last three decades of the 20th century developed only slowly, it however revealed the links between water shortage, hunger and population growth. This leads to a growing interest in the global hotspot regions and the potential for these areas to live up to the Millennium Development Goals (MDGs), which is the focus of this study.

We have shown that global food security in line with the diet composition of China, Brazil and Mexico, involving 3,000 kcal/day per person and 20% animal-based components, would imply some 60% larger food water requirements than at present. A world-wide *modernisation of agriculture* (including irrigation expansion), in the developing world, would bring down the additional water requirement and leave a summarized country-based estimate of net water deficit in water short regions of altogether 2,150 km^3/yr which represents some 45% of the total additional global water requirements.

The study has put a finger on a foreseen *carrying capacity overshoot* in countries hosting 70% of world population by 2050, if looked at from the perspective of current dietary tendencies shown in Figure 2, which include around 20% animal based food. We have shown the enormous unbalance caused by population growth and the problems regarding realism in the MDGs of hunger alleviation if environmental sustainability should be met. The world is moving towards a future where indeed 2/3 of the world population will be depending on the remaining 1/3 for supplying them with part of their food needs, so that they can feed their population at the assumed dietary level. This would necessitate more than doubling of today's trade-based virtual water transfer only 40 years from now, to compensate for foreseeable food water deficits.

With the present dietary tendencies (cf. Figure 2), global food security by 2050 is in other words developing into an issue of *massive food trade*. This highlights the fundamental importance of rising income in water short countries to make them able to import the food deficit for feeding their populations (Liu *et al*., 2009). Future research is however needed to clarify the realism of the necessary food surplus production in the well-watered regions for export to the deficit regions. This issue includes besides surplus agricultural production also the necessary infrastructure, transport and trade involved, but also proper global governance of the food trade system. But food security in some poor countries may still remain unresolved since they might not afford to import what is missing, unless they can secure an economic development that opens up a window of purchasing power. Half of these may in fact manage by steering away from the current international food demand tendency and solve by aiming at an Indonesian type diet, reducing the animal-based food component of the assumed diet. Others will –unless they can seek support to lift their economic capacity– depend on aid, or choose horizontal expansion wherever possible, or indeed endure continued undernourishment.

The scale of the challenges suggests that it would be wise to steer away from current dietary tendencies in terms of *water-consuming animal-based components*, especially from the assumed 20% towards the 5% considered satisfactory for human health. Animal-based food preferences have enormous implications in terms of water needs difficult to meet, of carrying capacity overshoot in water-short countries, and of expanding trade dependency of around 5,000 million people, and of exposing the most overpopulated countries to the risk of mass emigration.

The *food water deficit gap* behind the carrying capacity overshoot can be closed in two principal ways: from above in terms of bringing down the food needs by water productivity improvement, by low animal-based diet, and by loss reduction, should that be possible. Closure from below will involve different measures to bring additional water to the deficit countries by irrigation, trade/virtual water transfer, and cropping pasture lands. One may state that expected animal-based food preferences tend to threaten global food security, in the sense that they multiply the pressure in terms of consumptive water use on the water resources system. In terms of scales of the different measures to close the gap, trade and economic development to achieve purchasing power would be the most efficient activities next after agricultural modernisation, corresponding to 72% of the net water deficit gap. Cropping pasture and diet adaptation (bringing down the animal-based food component from 20% to 5%) would close another 26% of the gap. Remaining will be 2% of the gap representing food aid or undernutrition.

One key obstacle complicating global food security is the large scale of current food losses from field to fork. However, as shown in Table 3, even a loss-free production would not help the 6 most precarious countries (altogether some 200 million people).

5.2 *Importance of clear concepts and fresh courage to tackle core components*

There has in the past been a *poor conceptualisation* of water use. Looking back to the alarms generated already in the 1970s, it is evident that approaches to global food security have remained conceptually truncated. For some 30 years, the approach remained supply-oriented and for a long time technically oriented with focus on irrigation requirements. Only in the late 1990s did it become clear that most food was in fact produced by infiltrated rain (green water) rather than by irrigation water (blue water) except for certain regions with large scale irrigation This chapter has demonstrated the implications of adding to the analysis of future food security the new concepts of green water and virtual water. This made possible a fuller understanding of the water challenges and regional dimensions involved in feeding humanity in the future. We now need to make use of the many possible ways to combine blue and green water management, today referred to by the concept green/blue continuum (Vidal *et al*., 2010).

When analysing future global food supply, there is every reason to remember the wisdom formulated by the Nobel Laureate in Physics 1937, Sir Georg Paget Thomson: "All science depends on its concepts. These are ideas which receive names. They determine the questions one asks, and the answers one gets. They are more fundamental than the theories which are stated in terms of them".

Besides conceptual development it will be essential to also bring the *unspeakable* issue of *population growth* to the surface. Unless the poor and most water short countries can find ways to secure economic development enough for food import, emigration may be a non-neglectable threat. The world seems not yet to have realised the overloading of their natural resources in an unsustainable way, and that water availability is now a limiting factor in large parts of the world. The fact that the poorest countries with the most rapid population growth are located in the dry climate low latitude regions is an extremely serious dilemma. The longer it will take to reach the replacement level, the more difficult will it be to alleviate hunger. After all, more calories are equivalent to more water consumption, and the hungry and undernourished are primarily living in the water short regions of the world, moving towards a carrying capacity overshoot. Restraining the ongoing population increase is a fundamental key to limit the constantly increasing exploitation of natural resources and environmental degradation. Many developing countries are currently caught in a demographic trap by having developed far enough economically and socially to reduce mortality, but not far enough to quickly reduce fertility (Brown, 2009). Others have during the last decades rapidly falling birth rates (Rosling, 2010) and this is a positive sign that might possibly make the expected population increase come to halt earlier than the projected 9,000 million.

Already 40 years ago the father of the green revolution, Norman Borlaug, who passed away in September 2009 at the age of 95, made exactly this point in 1970 when he accepted the Nobel Peace Prize: "There can be no permanent progress in the battle against hunger until the agencies that fight for increased food production and those that fight for population control unite in a common effort" (Sachs, 2009).

6 CONCLUSIONS

In terms of country level food security, we may conclude:

– That global food security with present dietary tendencies develops into a 1/3–2/3 world of massive food trade from water surplus countries to almost 5,000 million people in countries with agricultural water deficit.
– The basic option for the economically more developed group of developing countries will either be to pay for food import allowing a 20% animal food level diet, or alternatively heading for a lower level to free economic resources for other more preferable purposes.
– That 17 poor countries without purchasing power to pay for import might however be left with food security problems and face a different set of options: half of them can be food self-sufficient by heading for only 5% animal food rather than the global tendency of 20%. To the other half, the only remaining choice stands between horizontal cropland expansion and aid, in order to avoid undernutrition and outmigration.

Other main conclusions are the following:

– That most future food production can take place on current croplands provided that agriculture in all countries be modernised to reduce avoidable water losses.
– That water productivity increases are implemented globally is extremely important. If today's water productivity would prevail till 2050, the global food water deficit would be twice the surplus, compared to our positive projections where the global surplus is twice as big as the deficit.
– That food transfers across national borders will have to grow considerably and be divided in two parts: a major trade flow to countries on an acceptable economic level, and some aid to avoid undernutrition of the poorest parts of the populations in the remaining water deficit countries.
– That it will be absolutely essential to generate economic development in poor countries to provide purchasing power to import the food required.
– That the ongoing trend with more and more water intensive diets in terms of animal food is a global environmental threat and must be restrained, and in developed countries reversed.
– That loss reduction will be essential; both water related losses by continued water productivity improvements, and the so far untapped possibility to reduce food losses in the chain from field to fork.

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