# Assessing the water challenge of a new green revolution in developing countries

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**This article analyzes the water implications in 92 developing countries of first attaining the 2015 hunger target of the United Nations Millennium Development Goals and then feeding a growing population on an acceptable standard diet. The water requirements in terms of vapor flows are quantified, potential water sources are identified, and impacts on agricultural land expansion and water tradeoffs with ecosystems are analyzed. This article quantifies the relative contribution from infiltrated rainwater/green water in rain-fed agriculture, and liquid water/blue water from irrigation, and how far water productivity (WP) gains can go in reducing the pressure on freshwater resources. Under current WP levels, another 2,200 $km^3 \cdot yr^{-1}$ of vapor flow is deemed necessary to halve hunger by 2015 and 5,200 $km^3 \cdot yr^{-1}$ in 2050 to alleviate hunger. A nonlinear relationship between vapor flow and yield growth, particularly in low-yielding savanna agro-ecosystems, indicates a high potential for WP increase. Such WP gains may reduce additional water needs in agriculture, with 16% in 2015 and 45% by 2050. Despite an optimistic outlook on irrigation development, most of the additional water will originate from rain-fed production. Yield growth, increasing consumptive use on existing rain-fed cropland, and fodder from grazing lands may reduce the additional rain-fed water use further by 43–47% until 2030. To meet remaining water needs, a cropland expansion of ≈0.8% $yr^{-1}$, i.e., a similar rate as over the past 50 years (≈0.65% $yr^{-1}$), seems unavoidable if food production is to occur in proximity to local markets.**

consumptive water use | food security | water productivity | water resource management

In a recent article on changes in the global pattern of vapor flows from the land surface to the atmosphere, Gordon *et al.* (1) stressed that the proportion of vapor flows in the global hydrological cycle will continue to increase over the next 50 years in efforts to meet food requirements of an additional 2–3 billion people and to reduce today's undernutrition. This article analyzes vapor flow changes expected from hunger alleviation efforts in developing countries in response to the United Nations (UN) Millennium Development Goals (MDG).

Population growth occurs almost exclusively in developing countries, annually adding 60 million to 80 million new inhabitants over the coming 20 years. There is a close link between hunger and poverty, with 70% of the world's 1.1 billion absolute poor living in rural areas, where the majority of the 850 million malnourished are hosted (2). Agricultural development remains key to economic growth in these countries (3). To meet the hunger goal, two priority regions have been identified in the UN MDG process: South Asia and sub-Saharan Africa (4), the same regions where Conway (5) raised concern over a future hunger gap when comparing projections of plausible irrigation development with market-based food demands.

As seen from Fig. 1 (2), the two priority regions share particular hydro-climatic challenges. They are largely situated in the zone with tropical savanna agro-ecosystems and are characterized by considerable challenges: seasonal rainfall, intermittent dry spells, recurrent drought years, high evaporative demand, and often inherently low-fertile soils vulnerable to erosion (6). Food crop yields are generally low in these regions. Sub-Saharan Africa never benefited from the Green Revolution of the 1960s and 1970s with high-yielding crop varieties, irrigation, fertilizers, and pest management. The result is extremely low cereal yields (oscillating ≈1 $t \cdot ha^{-1}$, ton/hectare) and merely 5% of agricultural land under irrigation. South and southeast Asia, on the contrary, were at the heart of the Green Revolution, with higher yields (at least twice as high as in sub-Saharan Africa; ref. 7) and large irrigation withdrawals amounting to >60% of agricultural water use. In regions supported by irrigation, many rivers are increasingly being depleted (8), and the potential for irrigation expansion is therefore limited.

The close link between lack of food- and water-related constraints is caused by the large volumes of water as vapor flow [evapotranspiration (ET)] required in plant growth, ranging on average between 1,000 and 3,000 $m^3 \cdot t^{-1}$ dry matter grain yield for the world's dominating cereal crops (9). We define vapor flow as green water flow or consumptive water use in biomass production. Consumptive green water flow in agriculture originates from either naturally infiltrated rainwater in the soil (the green water resource) or irrigation water from surface or groundwater sources (blue water resource) withdrawn from runoff flows (blue water flow) (1, 10).

The hunger challenge involves different population categories. The task of halving hunger by 2015 will involve lifting the dietary intake for part of the population of currently malnourished persons and providing adequate diets for a growing population (1). Analyses show that undernourishment approaches zero in a country when average calorie levels approach 3,000 $kcal \cdot cap^{-1} \cdot yr^{-1}$ (2). This average level, which corresponds to the level of food consumption that the Food and Agriculture Organization (FAO) assumes will be reached by 2030 (11), is used as the benchmark for hunger alleviation in this article.

Large investments in water resource management are thus linked to attaining the UN MDG on hunger and poverty (12), with the 2015 target of halving the proportion of malnourished and with the long-term goal of eradicating hunger (which we have set to 2030 here). A backcasting approach is applied, where

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Abbreviations: FAO, Food and Agriculture Organization; UN, United Nations; MDG, Millennium Development Goals; t/ha, ton per hectare; ET, evapotranspiration; WP, water productivity.

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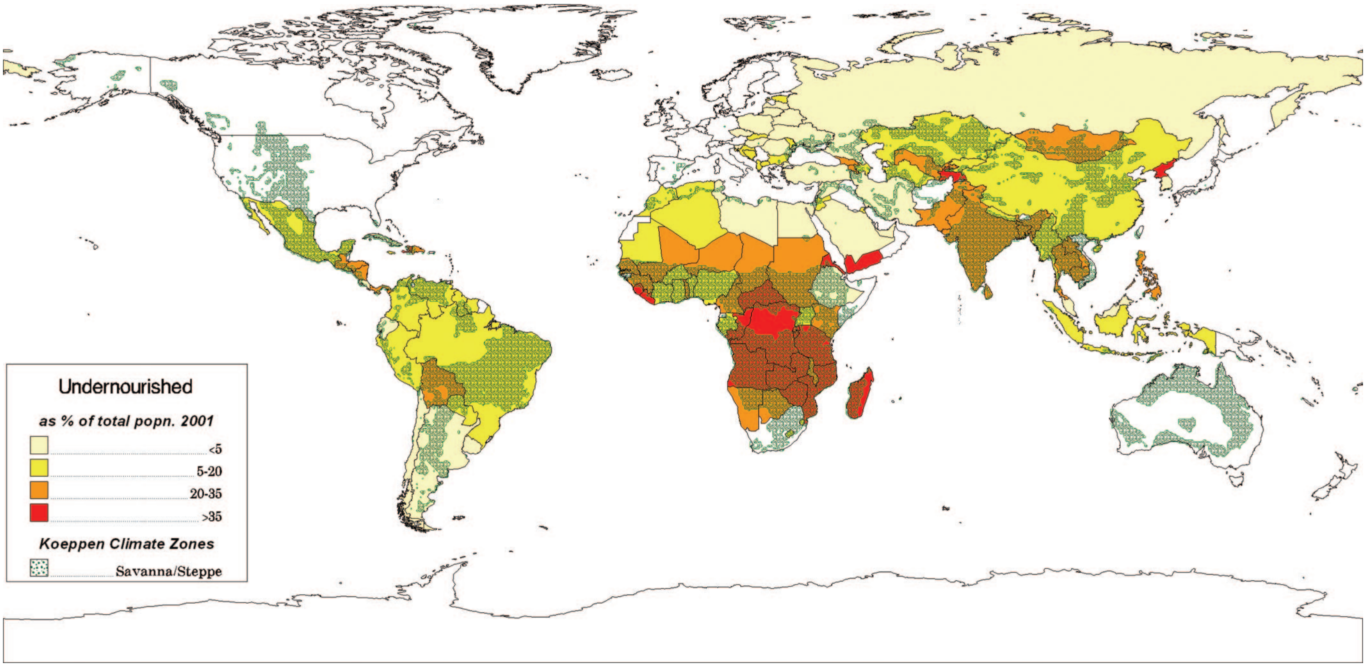


**Fig. 1.** World map showing the links between undernutrition and hydro-climatic preconditions. Prevalence of undernourished in developing countries is shown at the country level as the percentage of population 2001–2002. Hydro-climatic distribution of semiarid and dry-subhumid regions are shown in gray. These regions correspond to savanna and steppe agro-ecosystems, dominated by sedentary farming and subject to extreme rainfall variability and high occurrence of dry spells and droughts.

the water implications for societies and ecosystems of attaining these goals are assessed, and a plausible pathway for raising food and water productivity (WP) is analyzed.

## Results

**The Current Yield Gap: Taking a Water Balance Approach.** From an agro-hydrological perspective there is enough rainfall even in semiarid and dry-subhumid savanna agro-ecosystems to allow significantly increased yield levels. Field observations indicate a yield gap of a factor 2–4 between current farmers' yields and achievable yields in developing countries (12). This gap is supported by a water balance analysis of yield data, applying a green water crop model developed by Rockström and Falkenmark (13) (Fig. 2). The current low yields in a semiarid tropical agro-ecosystem are explained and manifested by on-farm blue water losses in terms of both surface runoff, limiting infiltration to the root zone, and percolation to groundwater (reduction in *y* axis), and on nonproductive vapor flow (evaporation), reducing the productive vapor flow component (plant transpiration) (reducing in *x* axis). At a generic level, if all water accessible in the root zone could be used productively, i.e., without nonproductive vapor losses and nutrient deficiency, the potential yield in the illustrated case would reach 3 t·ha$^{-1}$. If there also was no deep percolation, the potential yield would reach 5 t·ha$^{-1}$. If, finally, all local rain could be put to use without any farm-level water losses, the potential yield would rise to 7.5 t·ha$^{-1}$. In reality, among small-holder farmers, only a fraction of rainfall typically infiltrates, and only a small fraction of this water is taken up by the crop, resulting in low on-farm crop yields. Experimental yields in the same hydro-climate generate on the order of 4 t·ha$^{-1}$, and commercial yields often exceed 5 t·ha$^{-1}$ (6).

These facts suggest that there are no hydrological limitations to attain a doubling of yield levels, even in the savanna zone. This idea is supported by field observations showing that yields in small-holder tropical farming systems can be raised on average by 100%, and often by several hundred percent (14, 15). Supported by these analyses, we assess that food grain yields in developing countries can be raised from today's weighted average (yield in relation to agricultural area) of 1.5–2 t·ha$^{-1}$ (7) to 3.5–4 t·ha$^{-1}$ by 2030–2050.

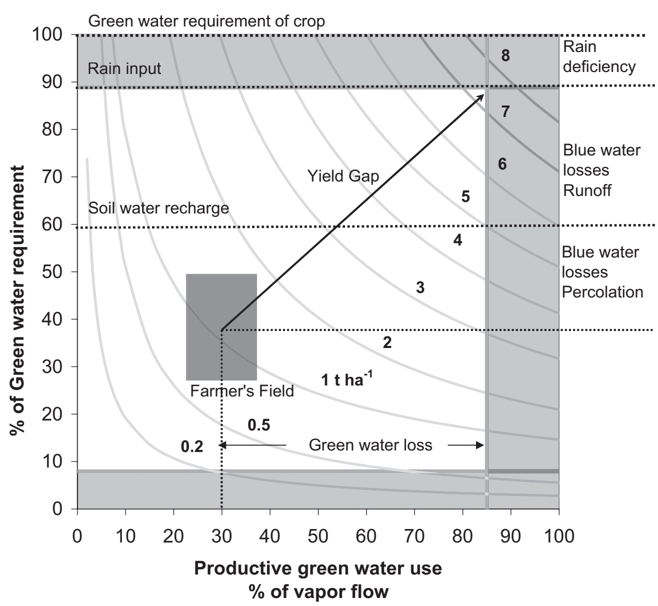


**Fig. 2.** Farm-level blue and green water balance analysis of the gap between actual and potential crop yields in terms of green water availability (percentage of rainfall that infiltrates in soil and returns as green vapor flow) (*y* axis) and productive green water use (percentage of transpiration of total vapor flow) (*x* axis). Lines show iso-lines of equal yield (t·ha$^{-1}$) and represent different combinations of flows in the on-farm water balance. The shaded square represents the observed hydrological range for on-farm rain-fed maize farming in semiarid locations in sub-Saharan Africa, yielding on average 1 t·ha$^{-1}$.

**Table 1. Estimated volumes of freshwater required to generate different components of human diets based on previous global assessments of water productivity in food-producing systems (16)**

| Food type | $m^3 \cdot kg^{-1}$ | $m^3 \cdot 1{,}000 \cdot kcal^{-1}$ |
|---|---|---|
| Cereals | 1.5 | 0.47 |
| Starchy roots | 0.7 | 0.78 |
| Sugarcrops | 0.15 | 0.49 |
| Pulses | 1.9 | 0.55 |
| Oilcrops | 2 | 0.73 |
| Vegetable oils | 2 | 0.23 |
| Vegetables | 0.5 | 2.07 |
| Average | | 0.53 |
| Used in paper | | 0.5 |
| Meat | | 4 |
| Dairy products | | >6 |
| Used in paper | | 4 |

**Water Consumed in Food Production.** Under current WP levels in agriculture (defined as $m^3$ of vapor flow per ton of edible dry weight of food, $m^3 \cdot t^{-1}$), our estimates, based on previous global assessments (6, 16), indicate that 0.5 $m^3$ of water is required on average to produce the equivalent of 1,000 kcal of vegetal food and 4 $m^3 \cdot 1{,}000\ kcal^{-1}$ of animal products (Table 1). More water is required to produce animal foods, because only part of the vegetal energy consumed by animals is transformed into meat, milk, or eggs. The values used here are equal or lower compared with earlier estimates (17–19). For animal products our estimates at the country level are lower, as we consider both cultivated feed (consuming more water) and feed from grazing lands (consuming less water) (16).

Considering the variations in present dietary composition at the country level, and current estimates of WP, results in an estimated 4,500 $km^3 \cdot yr^{-1}$ of water (as vapor flow) to produce food in the 92 developing countries [out of a global estimate of 6,800 $km^3 \cdot yr^{-1}$ for world food production (16), of which 1,800 $km^3 \cdot yr^{-1}$ originate from irrigated agriculture and 5,000 $km^3 \cdot yr^{-1}$ from rain-fed agriculture]. An average freshwater quantity of 1,300 $m^3 \cdot p^{-1} \cdot yr^{-1}$ will be required to produce a balanced diet of 3,000 $kcal \cdot p^{-1} \cdot d^{-1}$, with 20% calories from animal products (11). This quantity is 70 times more than the so-called basic water need (20), seen as necessary for drinking and household purposes. To attain the 2015 MDG target, an additional 2,200 $km^3 \cdot yr^{-1}$ would be required relative to 2002 (Fig. 3), which in itself is more additional water for agriculture than is currently consumed by irrigation in the world. By 2030, an additional 4,165 $km^3 \cdot yr^{-1}$ would be required, and 5,160 $km^3 \cdot yr^{-1}$ by 2050, to keep pace with a growing population.

**WP Improvement When Low Yields Increase.** A linear relationship is generally assumed between biomass growth and vapor flow (ET), which translates to a static or constant WP [in the range of 1,000–3,000 $m^3 \cdot t^{-1}$ for grains (9)]. Every new unit food thus requires an equivalent incremental new unit of water (21–24). Increasingly, it is recognized that this linear relationship does not apply for the lower yield range <3 $t \cdot ha^{-1}$ (6, 25) where essentially all small-scale farmers in developing countries operate (9). The reason is that improvements in agricultural productivity, resulting in yield increase and denser foliage, will involve a vapor shift from nonproductive evaporation ($E$) in favor of productive transpiration ($T$) and a higher $T/ET$ ratio as transpiration increases (essentially linearly) with higher yield (26). This vapor shift implies a nonlinear relation between WP and yield (Fig. 4), validated against a number of empirical field observations on grains in both tropical and temperate environments (27–34) (see

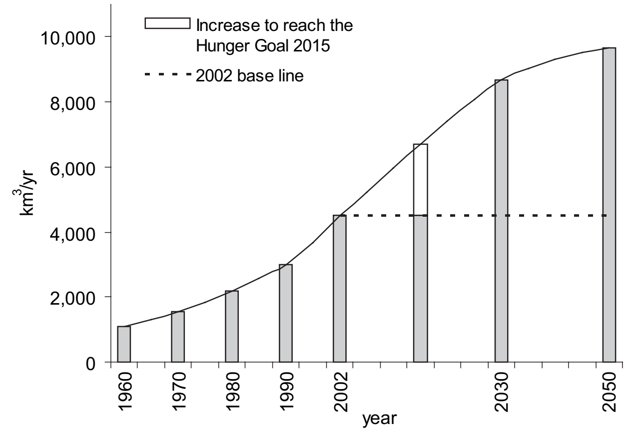


**Fig. 3.** Estimated water requirement for food production in 92 developing countries to fulfill the hunger goal target of the MDG by 2015 and to eradicated hunger by 2030 and 2050, based on current estimates of WP and future food consumption (7).

*Methods*). Applying this relation, which is surprisingly robust for different grains (35), across hydro-climatic zones and management systems, the projected yield increase from 1.5–2 $t \cdot ha^{-1}$ to 3.5–4 $t \cdot ha^{-1}$ corresponds to a WP improvement from ≈1,800 $m^3 \cdot t^{-1}$ to 1,200 $m^3 \cdot t^{-1}$, i.e., relative savings of 600 $m^3 \cdot t^{-1}$ of grain produced.

The potential for vapor shift is high in the MDG priority countries where a large portion of the vapor flow from crop fields is currently lost as nonproductive evaporation. For a poor farmer producing food at a typical yield of 1 $t \cdot ha^{-1}$, the crop requires on average 3,500 $m^3 \cdot t^{-1}$, whereas a doubling of the yield would improve WP to ≈2,000 $m^3 \cdot t^{-1}$. However, while the relative crop per drop improvement is substantial (from 7,000 $m^3$ to produce 2 $t \cdot ha^{-1}$ without WP change to 4,000 $m^3 \cdot ha^{-1}$, i.e., a relative saving of 3,000 $m^3 \cdot ha^{-1}$), the absolute water requirement increases despite improved WP with higher yield (from 3,500 $m^3 \cdot ha^{-1}$ at a yield of 1 $t \cdot ha^{-1}$ to 4,000 $m^3 \cdot ha^{-1}$ when harvesting 2 $t \cdot ha^{-1}$ in this example). This large relative WP improvement applies only for farming systems operating in the low-yield range, between 0 and 3 $t \cdot ha^{-1}$. Above 3 $t \cdot ha^{-1}$ the WP shifts from the nonlinear mode to the earlier assumed static mode, where each incremental yield increase occurs with a more or less constant

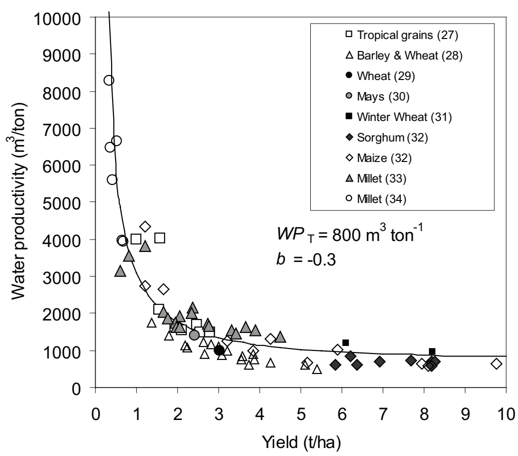


**Fig. 4.** Nonlinear relationship between WP and grain yields for cereal crops in tropical and temperate farming systems.

Table 2. **Total consumptive water use for food production and additional freshwater requirements (compared to 2002) to achieve the 2015 MDG hunger target (halve the proportion of hungry since 1992), and the MDG hunger goal of eradicating hunger by 2030 and beyond, indicating possible ways of covering those water requirements**

| Component | 2002 ($km^3 \cdot yr^{-1}$) | 2015 ($km^3 \cdot yr^{-1}$) | 2030 ($km^3 \cdot yr^{-1}$) | 2050 ($km^3 \cdot yr^{-1}$) |
|---|---|---|---|---|
| Total consumptive use | 4,500 | 6,700 | 8,660 | 9,660 |
| Additional requirements (static WP) | | 2,200 | 4,165 | 5,160 |
| Water savings nonlinear WP analysis (vapor shift and increased $T/ET$ ratio) | | 350 | 1,150 | 2,300 |
| Additional requirements (dynamic WP) | | 1,850 | 3,015 | 2,850 |
| Irrigation contribution (including system-wide irrigation efficiency) | | 270 | 520 | 725 |
| Remaining rain-fed contribution | | 1,580 | 2,500 | 2,125 |

WP. Given that the bulk of increased food demand occurs in tropical regions, the opportunity to improve WP simultaneously with yield growth is an important factor to consider in investments for agricultural intensification.

In our calculations, we have assumed reduced evaporation losses also for irrigated agriculture. With a relative improvement in WP, the 0.5 $m^3$ needed to produce 1,000 kcal of vegetal food would sucessively decrease to 0.38 $m^3$ per 1,000 $kcal^{-1}$, and the 4 $m^3$ needed to produce 1,000 kcal of animal products would decrease to 3.08 $m^3$ per 1,000 $kcal^{-1}$. The current dietary water requirement of 1,300 $m^3 \cdot p^{-1} \cdot yr^{-1}$ to produce 3,000 $kcal \cdot p^{-1} \cdot yr^{-1}$ would in 2050 be reduced to some 1,000 $m^3$ per person and year. This would result in a water saving by 2015 of 350 $km^3 \cdot yr^{-1}$, i.e., a 16% reduction of freshwater requirements compared with the previous scenario with no WP improvements. The water savings by 2030 and 2050 are larger, potentially reaching 1,150 $km^3 \cdot yr^{-1}$ or a 28% saving by 2030, and 2,300 $km^3 \cdot yr^{-1}$ or a 45% saving by 2050, compared with the static situation.

The WP improvement would thus potentially bring down the additional water requirements to attain the hunger alleviation goal to 1,850 $km^3 \cdot yr^{-1}$ by 2015 (in relation to 2002), to 3,015 $km^3 \cdot yr^{-1}$ by 2030, and 2,850 $km^3 \cdot yr^{-1}$ by 2050. In the period 2030–2050, the water saving, in fact, compensates for the additional water required to meet the population growth under conditions of food self-sufficiency. Despite a significant decrease, these amounts represent very large additional water requirements for food self-sufficient production in the developing world (assuming an adequate supply of nutrients). In the following we analyze how these requirements can be met.

**Irrigation: Adding More Blue Water.** The first question posed is how far irrigation can contribute to the additional freshwater required. Irrigation plays and will probably continue to play an important role in feeding the world. Current global vapor flow in irrigation is, as already indicated, on the order of 1,800 $km^3 \cdot yr^{-1}$, of which $\approx$1,400 $km^3 \cdot yr^{-1}$ occurs in developing countries (36, 37). Although irrigation expansion projections have been scaled down in recent years (38), opportunities still remain, particularly in sub-Saharan Africa. We have chosen to adopt an optimistic outlook for the potential expansion (11), based on an assumption of significant systemwide efficiency improvements (see *Methods*). Based on historical trends and these projections (2), we estimate that irrigation water may contribute an additional 270 $km^3 \cdot yr^{-1}$ of the estimated additional freshwater required for agriculture by 2015, i.e., a 19% growth compared with 2002 (1.4% growth per year). For the period 2015–2050, we estimate an additional irrigation contribution of 520 $km^3 \cdot yr^{-1}$ by 2030 and 725 $km^3 \cdot yr^{-1}$ by 2050.

The remaining water requirement will have to be covered by naturally infiltrated rainwater (green water). Our estimates indicate that such water will have to contribute up to 85% of the additional freshwater required relative to 2002, or an additional 1,580 $km^3 \cdot yr^{-1}$ by 2015, 2,500 $km^3 \cdot yr^{-1}$ by 2030, and 2,125 $km^3 \cdot yr^{-1}$ by 2050, compared with 2002. Table 2 summarizes the analyses so far.

**Contribution from Rain Over Grazing Lands.** The next question is the contributions from grazing lands to our estimates of dietary water needs. We differentiate between feed production on croplands and fodder production from permanent grazing lands. Our estimates suggest that two-thirds of the water to generate a desired diet of 3,000 $kcal \cdot p^{-1} \cdot d^{-1}$ currently originates from water to produce feed and fodder (with current WP, on average 1.2 $m^3 \cdot p^{-1} \cdot d^{-1}$ from vegetal food and 2.4 $m^3 \cdot p^{-1} \cdot d^{-1}$ from animal foods). Assuming this balance persists, 1,055 $km^3 \cdot yr^{-1}$ of the 1,580 $km^3 \cdot yr^{-1}$ of additional water by 2015 would originate from different feed/fodder sources to produce animal foods, with the remaining 530 $km^3 \cdot yr^{-1}$ for crop-based vegetal foods.

Based on FAO food balance sheets (39) the calories from animal products in current diets were divided into two main categories of livestock systems: (*i*) systems fed from nongrazing/cultivated fodder (poultry, egg, pork), and (*ii*) systems based partly on grazing (dairy, beef, mutton, and goat). In the next step, the fodder in the "partly grazing" category was split into grazing-based and cultivated fodder based on information from the FAO (11). This simple analysis suggests that grazing will contribute fodder equivalent to 370 $km^3 \cdot yr^{-1}$ of the water requirement by 2015 (580 $km^3 \cdot yr^{-1}$ by 2030 and 500 $km^3 \cdot yr^{-1}$ by 2050).

This leaves 685 $km^3 \cdot yr^{-1}$ of water to produce grain feed for livestock (1,055 $km^3 \cdot yr^{-1}$ minus 370 $km^3 \cdot yr^{-1}$). In total, including crops for food and feed, an estimated 1,210 $km^3 \cdot yr^{-1}$ (685 $km^3$ feed plus 530 $km^3$ food) by 2015 (1,910 $km^3 \cdot yr^{-1}$ by 2030 and 1,630 $km^3 \cdot yr^{-1}$ by 2050) will have to originate from cultivated rain-fed crop lands.

**Contribution from Rain Over Current Farmland.** The next question is how much of the 1,210 $km^3 \cdot yr^{-1}$ needed already by 2015 can be

**Table 3. Yield scenario, corresponding water productivity assessments, and estimated growth in water consumption on cropland**

| Component | 2002 | 2015 | 2030 | 2050 |
|---|---|---|---|---|
| Average crop yield ($t \cdot ha^{-1}$) | 2 | 2.5 | 2.9 | 4 |
| WP ($m^3 \cdot t^{-1}$) | 1,770 | 1,580 | 1,360 | 1,200 |
| Water consumption ($m^3 \cdot ha^{-1}$) | 3,540 | 3,950 | 4,000 | 4,800 |
| Increased consumption ($m^3 \cdot ha^{-1}$) | | 400 | 450 | 1,260 |

Increased consumption is estimated in relation to 2002.

met on current rain-fed cropland. Current rain-fed cropland in developing countries is estimated at 0.9 billion ha (7, 40, 41). Based on the earlier analysis of the potential for increasing rainwater capture on current tropical cropland (Fig. 2), we estimated that it is possible to increase yields from the current average range of 1.5 to 2 $t \cdot ha^{-1}$ to an average of 2.5 $t \cdot ha^{-1}$ by 2015 and to attain average yields of 4 $t \cdot ha^{-1}$ in 2050 (Table 3).

This modest step in terms of improved agricultural and WP will be enough to contribute $\approx$360 $km^3 \cdot yr^{-1}$ (increased consumption of 400 $m^3 \cdot ha^{-1}$ on 0.9 billion ha of current cropland). This increased rainwater capture corresponds to a contribution of $\approx$40 $mm \cdot ha^{-1} \cdot yr^{-1}$, which should be compared with the average annual rainfall of 500–1,000 mm in most semiarid and dry-subhumid tropical-regions. However, an additional infiltration of rainwater might leave a reduced contribution to runoff generation and reduce the amount of streamflow (blue water flow) available downstream.

**Cropland Expansion.** After making adjustments for the various contributions of irrigation, rain over grazing lands and better capture of rainfall over rain-fed croplands, and using optimistic assumptions about WP improvements and productivity gains on current crop land, a water requirement to attain the 2015 target of $\approx$850 $km^3 \cdot yr^{-1}$ (1,210 $km^3 \cdot yr^{-1}$ − 360 $km^3 \cdot yr^{-1}$) remains unmet and may have to be covered by expanding croplands, primarily into tropical forests and grasslands. We estimate that this unmet need would correspond to an average expansion rate of 1.3%$\cdot yr^{-1}$ for croplands in developing countries during the period 2002–2015, and a rate of 0.7% $yr^{-1}$ for the period 2015–2050, resulting in an average expansion rate of 0.8% $yr^{-1}$ over the coming 50 years. This need suggests a continued expansion rate of agriculture at a similar rate over the coming 50 years as over the past 50 years, when the expansion rate averaged 0.65% $yr^{-1}$ in developing countries (11). Our analysis points at a large increased pressure on agricultural land over the short term (next 10–20 years) if the MDG are to be met through local food production. A trend toward more rapid expansion in developing countries can be seen over the past decades [from 0.5% $yr^{-1}$ in the 1970s to 0.7% $yr^{-1}$ from 1980 to 2000 (7)]. Our estimates indicate an opportunity, through agricultural and WP improvements, to lower the average expansion rate of agricultural crop land over the period 2015–2050. Even so, these expansion rates imply the need for an overall cropland expansion of altogether some 454 million ha up to 2050, i.e., an expansion of the order of 50%.

**Tradeoffs Against Natural Ecosystems.** Because water is a finite resource and the water cycle is the bloodstream of the biosphere (42), competition with the water requirements of ecosystems will be unavoidable, both in terrestrial ecosystems due to horizontal expansion of croplands and in aquatic systems due to impacts on streamflow from altered vapor flow (in our analysis another 360 $km^3 \cdot yr^{-1}$ by 2015 from current rain-fed land in developing countries) and reduced return flows from more efficient irrigation (in our analysis another 270 $km^3 \cdot yr^{-1}$ used for irrigation by 2015). To illustrate future tradeoff scenarios, Fig. 5 puts present and future water requirements for food production (after productivity increase) in relation to an indicative analysis of current freshwater use by all other terrestrial and aquatic ecosystems for three developing countries. These country examples are chosen to illustrate the challenge facing three categories of developing countries (countries with significant blue water dependence on

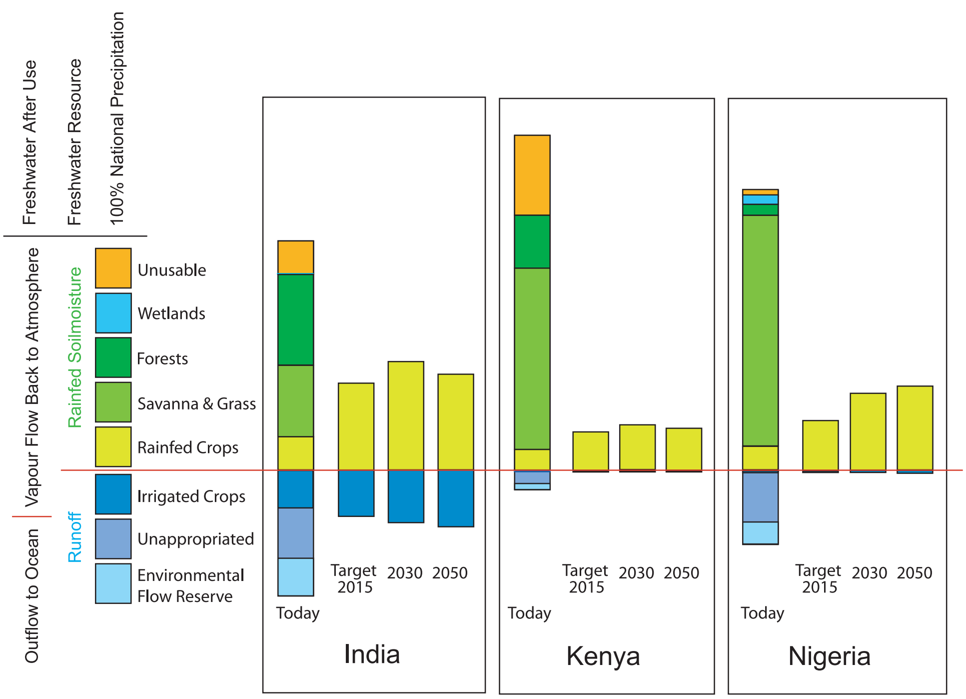


**Fig. 5.** Indicative analysis for three developing countries of freshwater use by terrestrial and aquatic ecosystems (column Today) as compared with water requirements (after considering WP increase) to reach the 2015 MDG target and eradicate hunger by 2030 and 2050.

irrigation today, e.g., India; countries with relatively ample water resources subject to rapid growth in demand, e.g., Nigeria; and water-scarce countries with high dependence on green water use, e.g., Kenya).

It is clear that even if every single drop of blue water would be turned into food production, the nations' runoff would not be enough to meet the additional water requirements. In such situations expansion into other terrestrial ecosystems will be inevitable. It is important to note though that the analysis in Fig. 5 is indicative only because it is based on weak land-use data at the national level, with difficulties in distinguishing particularly among cropland, grazing lands, and grasslands. This is an important area of future research needs.

## Discussion

In summary, huge volumes of additional freshwater will be required to produce the food needed to eradicate hunger in the 92 developing countries analyzed, which, even after considering crop per drop improvements in agriculture, amounts to 1,850 $km^3 \cdot yr^{-1}$ by 2015. Irrigation may contribute 270 $km^3 \cdot yr^{-1}$, leaving $\approx$1,600 $km^3 \cdot yr^{-1}$ to be met from other sources. This freshwater can, except from grazing lands, only come from four sources: (*i*) capturing additional local rain, (*ii*) horizontal expansion of agriculture, i.e., tradeoffs with terrestrial ecosystems, (*iii*) imports of food from elsewhere, and (*iv*) changes in diets, i.e., lower $kcal \cdot p^{-1} \cdot d^{-1}$ intake and/or more vegetarian diets than assumed here. The most likely scenario is a combination of these four, where tradeoffs with ecosystems will be unavoidable.

Because of the unpredictability of factors influencing water requirements, such as diets, population growth, and climate change, our study merely provides indicators of the increase in water required to achieve the goal of hunger alleviation in the developing world. Climate change is projected to increase variability in rainfall, with more dry spells, droughts, and floods, and reduce rainfall levels in many developing regions, which will complicate MDG achievement further (43, 44). Our diet-based approach gives lower values than the earlier study of Postel (23). She estimated that already in 1995 the minimum water requirement for the global crop harvest was 3,200 $km^3 \cdot yr^{-1}$ to which has to be added the water consumed on grazing lands, estimated at 5,800 $km^3 \cdot yr^{-1}$. Our 2050 projections (9,660 $km^3 \cdot yr^{-1}$ = 4,500 $km^3 \cdot yr^{-1}$ today + 5,160 $km^3 \cdot yr^{-1}$) are comparable to recent estimates by the International Water Management Institute (IWMI), indicating that global water requirement will have to increase from the current 7,200 $km^3 \cdot yr^{-1}$ to 11,000–13,500 $km^3 \cdot yr^{-1}$ (45). The irrigation assumptions in this study are as already indicated optimistic. While we assumed an additional 520 $km^3 \cdot yr^{-1}$ by 2030, FAO's estimate is 290 $km^3 \cdot yr^{-1}$, IWMI's 446 $km^3 \cdot yr^{-1}$, and Shiklomanov's (46) 609 $km^3 \cdot yr^{-1}$.

This article has analyzed the water implications of self-sufficient food production in the developing world. Food trade can release pressure from local water tradeoffs. Sub-Saharan Africa and east and southeast Asia already at present depend on cereal imports (a net import of 13% of production) (7). If assuming that this level of import dependence continues in the future, the horizontal expansion would be reduced from 1.3% $yr^{-1}$ to 1.1% $yr^{-1}$ until 2015, and from 0.8% $yr^{-1}$ to 0.7% $yr^{-1}$ over the entire period until 2050. Trade can be of particular importance during the first two decades, i.e., when demand for food grows rapidly and before agricultural and water productivities have been fully achieved. Food trade is a socioeconomically and politically very complex issue, particularly in poor countries depending on agrarian economies, rendering its role in supporting hunger and poverty alleviation uncertain.

As shown in the analysis, the evolution of diets, particularly the portion of animal products, has a large effect on freshwater consumption. Our estimates indicate differences of a factor of eight in terms of consumptive water use for animal-based calories, compared with vegetarian products (on average 0.5 $m^3 \cdot 1{,}000\ kcal^{-1}$ compared with 4 $m^3 \cdot 1{,}000\ kcal^{-1}$). For animal products, our estimates are relatively conservative compared with earlier estimates (17, 47) and are thus in the lower range. This tendency is a result of trying to incorporate the proportion of animal products produced on grazing lands, where it is difficult to account for the vapor flow required to sustain fodder production. This area needs further research, including opportunity costs of using rainfall for other purposes than sustaining fodder grasses in free-grazing systems, and systems analyses on the ecological functions (other than fodder) sustained by vapor flow in grasslands.

## Conclusions

This article has clarified the hydro-climatic predicament behind the hunger goal of the UN Millennium Development Project. The poorest countries subject to the largest hunger alleviation challenge, the MDG hot-spot countries, tend to be situated in regions where freshwater plays a fundamental role in determining the livelihoods of poor people. They are subject to extreme rainfall variability in hot tropical savanna regions experiencing recurrent water scarcity. This analysis indicates that meeting the 2015 target will require massive additional volumes of freshwater to produce food, a 50% increased vapor flow in agriculture as compared with today. With unchanged WP, the water required for food production would have to double from today's 4,500 $km^3 \cdot yr^{-1}$ to 9,660 $km^3 \cdot yr^{-1}$ in 2050, which means that an additional 5,200 $km^3 \cdot yr^{-1}$ would have to be appropriated, causing further degradation of ecosystems.

Irrigation will continue to play an important role in feeding the world and opportunities for expansion still remain, particularly in sub-Saharan Africa where >95% of the agriculture is rain fed. In this analysis we have adopted an optimistic outlook and expect an irrigation expansion beyond 2015 at the same pace as population growth in each country. We also suggest that it may in fact be possible to escape from at least half of the huge additional water requirement in agriculture, through (*i*) WP improvements in rain-fed and irrigated agriculture (green water loss reduction in Fig. 2), and (*ii*) large efforts to improve rain-fed agriculture (better use of local rain).

Still, a large challenge remains (850 $km^3 \cdot yr^{-1}$), which, if food production is to occur in the country itself, can be attained only through continued land use conversions from forests and grasslands to agricultural land. Our analysis confirms the trend over the past 50 years, suggesting that the historic growth rate of 0.65% $yr^{-1}$ in developing countries would have to continue roughly at the same pace over the coming 50 years (on average 0.8% $yr^{-1}$). This is a high risk, as shown by the Millennium Ecosystem Assessment (40), where agricultural land use expansion was identified as the major driver behind large losses of ecosystem services from natural ecosystems. This raises the need for weighing tradeoffs between local social and economic development and environmental sustainability.

As a consequence, it is imperative that development efforts have a stronger focus on how to manage land and water resources to enable increases in food production. This is critical, as 70% of the poor people live in rural areas. These are the people in focus of the MDG. The strong current focus on irrigation development will evidently have to be balanced with new policies and investments on how to improve rain-fed agriculture, which will, by far, provide the bulk of food to attain hunger alleviation. Results can be achieved, as the water is largely available, and research shows that know-how, technologies, and management systems, appropriate to local rural communities, exist and could be successfully adapted and adopted if the right investments, capacity-building efforts, policies, and legal frameworks are put in place.

## Methods

Water requirements for food production are calculated at country level for each of the 92 developing countries with available data within FAO and UNstat (7). The analysis is divided into three time steps: the MDG target year of 2015 (when the proportion of hungry should be halved as compared with 1992) (48), the year 2030 (when we assume hunger eradication is accomplished), and finally the year 2050 (when world population has stabilized ≈9 billion).

**Quantifying the Hunger Eradication Challenge.** Population figures for all years are taken from FAOstat (7). The proportion of undernourished in 1990 was taken from UNstat and based on available data for 1990–1991. The most recent complete set of population data, 2001–2002, was used to assess the current situation. Present national dietary energy supply per capita and animal protein levels were taken from the FAO food balance sheets (39).

Rising incomes and urbanization are driving forces behind changed life styles and diet patterns in developing countries. The food component originating from animals, as meat, dairy, and eggs, is critical when analyzing future diets. Meat consumption per capita has doubled since the mid-1970s (11). Almost the entire global population increase in developing countries of 2.5 billion by 2050 is expected to take place in urban areas and already by ≈2015 these countries will have an urban majority (41). We have assumed a final calorie target by 2030 of 3,000 $kcal \cdot p^{-1} \cdot d^{-1}$ out of which 20% comes from animal products (600 $kcal \cdot p^{-1} \cdot d^{-1}$) (2). Countries with higher animal calorie content already at present will remain on that level. For the 2015 target year, nourished people get 3,000 $kcal \cdot p^{-1} \cdot d^{-1}$ and the animal calorie content is increased from the present level up to 20%. The undernourished are estimated to eat 1,700 $kcal \cdot p^{-1} \cdot d^{-1}$ (an approximation of the basic human energy need), with an animal calorie content equal to present average for each country. Between 2002 and 2015 and 2015 and 2030 the number of persons and diets to be considered for each country in the analysis thus include (*i*) part of the undernourished to be upgraded to fully nourished, (*ii*) the additional population that needs full diet supply, and (*iii*) the rest of the population that gets a stepwise diet improvement.

**WP Estimates.** Changes in WP as a result of yield improvements are quantified by using the approach developed by Rockström (9). Building on the work by Novak (49), who developed a simple natural logarithmic model to explain the progressive decline in $E/ET$ with increased leaf area development, and the water use efficiency analysis by Gregory *et al.* (50), a simple WP function was developed (and calibrated against empirical field data):

$$\mathrm{WP} = \frac{\mathrm{WP}_T}{(1 - e^{bY})}, \qquad [1]$$

where WP is green WP (ET flow, $m^3 \cdot t^{-1}$), $WP_T$ is productive green WP ($T$ flow, $m^3 \cdot t^{-1}$), $b$ is a constant, and $Y$ is grain yield ($t \cdot ha^{-1}$). $WP_T$ was set to 800 $m^3 \cdot t^{-1}$, which is a representative value for cereals (13, 26, 35). The constant $b$ determines the rate of decline in evaporation with increased crop canopy, and therefore also the yield level at which $E/ET$ reaches its minimum. This minimum $E/ET$ level also represents the yield level above which the WP-yield relation tends to fall back to the static mode, often assumed valid over the whole yield range. A fully static mode is reached at ≈5–7 $t \cdot ha^{-1}$, which corresponds to cropping systems with a dense canopy cover (leaf area index exceeding 3 $m^2 \cdot m^{-2}$). Static WP is, in other words, only applicable at yield levels generating high canopy cover.

**Deduction for Irrigation Expansion.** Projections of future water withdrawals for irrigation have been downscaled over the past decades as a result of an observed decline in irrigation expansion (11) and growing concerns over social impacts of large reservoir projects and needs to safeguard environmental water flows (51).

The analysis considers improvements in irrigation efficiency [the ratio (%) of consumed to withdrawn water] to separate withdrawals from actual consumptive use when estimating the contribution of irrigated agriculture to produce food. A distinction is further made between irrigation efficiency at the system level [$Cs$ (%)] and efficiency as we understand it here, i.e., the proportion of irrigation water withdrawals that is consumed on the cropped land (the percentage of water supply contributing to crop growth, $Cc$). This distinction highlights two principal means of raising irrigation efficiency. The first by assuring that more of the withdrawn water reaches the rootzone (i.e., by reducing evaporation losses in storage and conveyance), which may improve system level efficiency, $Cs$, or keep $Cs$ relatively constant, by increasing water available for consumption by the crop [raising the ratio of crop to system level efficiency ($Cc/Cs$)]. The other principal strategy is to raise the crop water uptake capacity of the irrigated cropping system (raise $Cc$). While $Cs$ generally is relatively high (on the order of 70–75%), as it includes evaporative losses from reservoirs and conveyance, $Cc$ is generally low, on the order of 30–40% (47). In this article we have assumed that $Cc = 70\%$. This is thus an optimistic assumption. We have, however, accepted this approximation to arrive at the maximum contribution from irrigation in relation to the consumptive water use required for food production.

**Ecosystem Tradeoff Analysis.** The tradeoffs between water use for food and ecosystems are analyzed by quantifying the volumes of water required to sustain terrestrial ecosystems (green water use) and aquatic ecosystems (blue water flow). These quantifications are compared with the analysis of consumptive water use for agriculture (after considering WP improvements) and availability of rainfall. Water consumed by major terrestrial biomes, i.e., forests, wetlands, and grasslands, was calculated from estimates of annual ET to sustain respective biomes (based on ref. 16) and multiplied with the land area occupied by those biomes at a country level. Rain over urban areas and deserts was considered unusable. Water consumed by irrigated crops has been taken as the withdrawal for agriculture, and the potential for irrigation expansion was estimated after leaving an unappropriated residual streamflow of 30% reserved for environmental water flows (8).


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