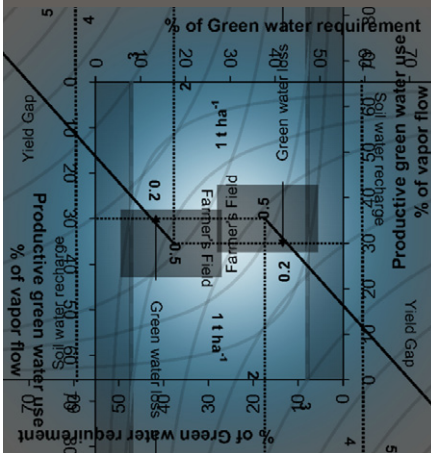


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To ensure global food security, crop production must outpace human population growth significantly during the next 40 yr. This review makes the case that this challenge can largely be met by optimizing the management of “green water” (soil water directly available to plant roots), an often overlooked resource whose annual global flow in fact matches that of all the rivers in the world flowing to the sea.

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Green Water and Global Food Security

It is widely understood that crop production must increase at least twice as fast as human population growth during the coming 40 yr to meet global food demand. Tested strategies for achieving this goal have not yet emerged, but some stipulations to guide in the search for them can be made. Adverse ecological impacts of land conversion to agricultural use and freshwater withdrawals for irrigation will strongly limit the viability of these two traditional approaches to increasing crop production, whereas abundant opportunity exists for optimizing soil water availability to and consumption by rainfed crops to increase their yields by twofold or more. This optimization, however, will require major campaigns in multidisciplinary basic research on positive plant–soil feedbacks that increase crop biomass by influencing the rhizosphere, through which 40% of the global freshwater flow passes annually.

*But if the soil breathes steaming vapors out,
Drinks moisture in, and when it wants to, breathes
The moisture out again, and if it's always
Green with the greenness of its grasses and
Never corrodes the blade of the plow with rust,
Then that's the place to drape your flourishing vines
Upon your elms, the place that will produce
Rich olive oil, the place (as the tilling will show)
That makes the plowing easy for the beasts
Because the soil is easy for the plow.*

—Publius Vergilius Maro (Virgil), Georgics, Book II (Ferry, 2005)

Despite a decline in growth rate by almost half during the past 40 yr, estimates of the global human population place it at 8 billion in 2024, with more than 9 billion expected by 2050 (Roberts, 2011; Tilman et al., 2011). This latter figure represents an increase of the current world population by about 30%, but the corresponding percentage change in food crop production to meet projected world demand will be much larger because it is driven by not only population growth but also personal income growth (Kearney, 2010; Tilman et al., 2011). Current analyses indicate that, to accommodate both of these upward socioeconomic trends, food crop production has to increase by 50 to 100% during the next 40 yr. That is, it must at least double the percentage change in population (de Fraiture et al., 2009; Hanjra and Qureshi, 2010; Gregory and George, 2011; Tilman et al., 2011). Moreover, as will emerge from arguments to be made in the next section, this large relative increase in food crop production will have to come mainly from increasing crop yield per hectare planted—crop intensification—not from converting more land to agricultural use. The challenge posed becomes even more daunting when considered in light of the evident stagnation or even decline in food crop yield increases over the past decade along with the dramatically increasing competition for resources from nonfood crops, particularly biofuels (Hanjra and Qureshi, 2010; Foley et al., 2011; Gregory and George, 2011).

♦ Framing the Challenge: Constraints

One useful way to approach a challenging problem is to establish the conditions under which any viable solution of it must operate. For the problem of determining ways to increase food crop production sufficiently to meet global demand, the results of recent detailed studies of land and water use worldwide, along with their ecological impacts, lead to three constraints that, in all likelihood, will narrow the range of possible alternatives. One of these constraints limits land conversion, as noted above; another limits agricultural water withdrawals, while the third one reveals a key facet of the consumptive use of water by croplands.

Constraint 1: Land Conversion for Crop Cultivation is Nearing its Planetary Limit

Cropland and pastureland together occupy about 38% of the ice-free global terrestrial surface, this having been achieved at the expense of losing 70% of the grassland, 50% of the savanna, 45% of the temperate deciduous forest, and 27% of the tropical forest biomes that existed before the advent of agriculture (Foley et al., 2005, 2011). The ecological impacts of native biome conversion to croplands, which now occupy 12% of the ice-free global terrestrial surface (Foley et al., 2011), are especially severe. For example, more atmospheric nitrogen is now converted for agricultural purposes to reactive and, therefore, potentially pollutant, forms of nitrogen than in all natural processes combined (Rockström et al., 2009c). The geographical upper limit on land conversion for crop production as prescribed by suitability for cultivation is about 22% of the global land surface (Smith et al., 2010); however, Rockström et al. (2009b, 2009c) have concluded from their preliminary assessment of ecological impacts (e.g., nutrient pollution, biodiversity loss, water resource depletion) that a much smaller “planetary boundary” must be imposed on the future expansion of croplands, eventually to limit them to occupy no more than 15% of the ice-free global terrestrial surface. In proposing what amounts to a strong constraint on the ways that crop production may be increased in the coming decades, Rockström et al. (2009c) remark that “humanity may be reaching a point where further agricultural land expansion at a global scale may seriously threaten biodiversity and undermine regulatory capacities of the Earth System.” A concern very similar to this was expressed in a recent position paper on “planetary tipping points” by Barnosky et al. (2012), who called for “increasing the efficiency of existing means of food production and distribution instead of converting new areas.”

Much to the point of the present paper, the careful analysis of global land-use trends by Smith et al. (2010) indicates that only about one-fifth of the increased crop production required to meet global food demand during the next 40 yr can viably be achieved by land conversion, this occurring mainly in Sub-Saharan Africa and Latin America. The estimate made by Smith et al. (2010), resonating with a detailed analysis of alternatives for meeting global food demand published by Tilman et al. (2011), will be sharpened by major ongoing improvements in the assessment of global croplands (Fritz et al., 2013). However, the estimate of one-fifth already may be too high, since the two regions named above tend to incur a very high “carbon debt” [i.e., the ratio of the change in carbon stock from land conversion (carbon stock in cropland minus that in the prior natural vegetation) to the annual crop yield (West et al., 2010)]. West et al. (2010) pointedly conclude from their global carbon debt analysis that, “particularly in the tropics, emphasis should be placed on increasing yields on existing croplands rather than clearing new lands.”

Constraint 2: Blue Water Use by Croplands is also Nearing its Planetary Limit

“Blue water” is a picturesque term referring to water that flows in streams and rivers, is stored in lakes and reservoirs, or is pumped from aquifers (Falkenmark and Rockström, 2004, 2006; Rockström et al., 2009a).

Blue water, of course, is extensively withdrawn for use in irrigated agriculture (Strzepek and Boehlert, 2010), which currently accounts for about 90% of the global consumptive use of this water resource, also termed the “blue water footprint” (Mekonnen and Hoekstra, 2011). This is a very large consumptive use, but irrigated croplands also produce nearly 40% of the global food supply (Rost et al., 2008; Hanjra and Qureshi, 2010). Determining how much blue water should be allocated to the nonagricultural biosphere is thus an abiding dilemma (Hanjra and Qureshi, 2010; Strzepek and Boehlert, 2010).

Hoekstra et al. (2012) have recently made a significant new overture in the ongoing debate by adopting a precautionary principle setting 20% of the natural runoff in a region as the upper limit of human consumptive use, where “natural runoff” is defined as the sum of the observed runoff plus the human consumptive use that has reduced runoff below the value it had in the absence of such use. This precautionary limitation in effect defines an environmental flow requirement (Strzepek and Boehlert, 2010). Accordingly, human consumptive use that does not leave at least 80% of the natural runoff in a region available for reuse is deemed to pose a serious risk to the health of ecosystems served by the runoff (Hoekstra et al., 2012). This limit of 20% on consumptive use is provisional, as is the case for any application of the precautionary principle, but it should be noted that more than 20% of a natural runoff may be withdrawn, so long as the resulting consumptive use remains below 20% of the natural flow.

Rockström et al. (2012) highlight the importance of these considerations by pointing out that current blue water withdrawals have already prevented the flows in about one-fourth of the perennial rivers in the world with ocean outlet from ever reaching their destination or, if they still do, to reach it only some of the time. In addition, major inland lakes on the planet are drying out. These hydrologic trends have in fact led to a proposed “planetary boundary” prescribing that any additional blue water consumptive use be limited to less than two-thirds of the current global blue water consumptive use (Rockström et al., 2009b, 2009c), although it is recognized that this limit also may prove to be too high when human uses of blue water that compete with agriculture (e.g., drinking water) are projected in detail (Molden, 2009; Strzepek and Boehlert, 2010). Rockström et al. (2012) fuel the issue by estimating future blue water needs for both irrigated agriculture and managed carbon sequestration, concluding from their estimates that expected increases in these two competitive uses alone would eventually exceed the proposed planetary boundary for blue water consumptive use. Suweis et al. (2013) recently added gravity to this perspective by showing that many areas of the world are near to or have already exceeded the human population that can be sustained by the blue water they have available for food production.

Building on the precautionary principle described above, Hoekstra et al. (2012) have offered a new quantitative indicator of “blue water scarcity” to supplant previous indices of blue water stress, such as the ratio of blue water withdrawal to renewable supply, by one they claim can be measured not only more accurately than the others but

also at a variety of temporal and spatial scales. Instead of blue water withdrawal, they propose using the blue water footprint, and instead of renewable supply, they propose using 20% of natural runoff, now defined as the “blue water availability,” i.e., the nominal consumptive use they assume can be borne without major ecological impact. When the ratio of these two consumptive use variables, evaluated for a chosen spatial scale (say, that of a river basin) over a chosen time-period (say, monthly) and expressed as a percentage, is less than 100%, Hoekstra et al. (2012) deem the blue water scarcity to be “low,” but when the ratio exceeds 200%, blue water scarcity is termed “severe,” meaning that more than 40% of the natural runoff is being consumed by humans, with consequent high risk of ecological decline.

Hoekstra et al. (2012) determined blue water scarcity for more than 400 river basins worldwide using monthly hydrologic data and suitable models. These river basins represented about two-thirds of the global population and three-quarters of the irrigated regions of the world. The blue water footprint in the basins comprised agricultural, domestic, and industrial consumption, with agriculture turning out to account for 92% of the global footprint. In about half of the river basins examined, representing 2.7 billion people, blue water scarcity was found to be “severe” during at least 1 mo of the year. In about 1 out of 12 of the basins, representing 500 million people, blue water scarcity was “severe” for at least 6 mo of the year, and in 12 of the river basins, “severe” blue water scarcity was experienced all year long. Hoekstra et al. (2012) concluded that “our results underline the critical nature of water shortages around the world.” Taking this perspective, one may conclude that meeting global food demand in 2050 by a major expansion of cropland irrigation, even if it were technologically feasible, would, like a major expansion of land conversion to cropland, incur the risk of substantial ecological decline, not to speak of severe depletion of blue water resources for competing domestic and industrial uses (Strzepek and Boehlert, 2010; Rockström et al., 2012).

Constraint 3: Most of the Water Consumed by Croplands is Green Water

“Green water” is the hydrologic complement of blue water (Falkenmark and Rockström, 2004, 2006). It is water in soil that remains potentially available to plant roots and the soil biota after precipitation losses to runoff and deep percolation have occurred (Rockström et al., 2009a). Nonagricultural ecosystems currently consume about three-fourths of the global green water flow, with the remaining one-fourth partitioned equally between croplands and pasturelands (Rost et al., 2008). Green water flows, aside from those induced by soil water redistribution, take place by evapotranspiration, so green water use by ecosystems is by definition wholly a consumptive use. The global flow of green water accounts for about 65% of the total global flow of any freshwater, green or blue (Rost et al., 2008; Rockström et al., 2009c), and the virtual flow of green water induced by trade in food commodities accounts for 85–88% of all such virtual flows (Konar et al., 2012; Hoekstra and Mekonnen, 2012). The global flow of green water by transpiration alone approximately matches that of all the rivers in the world flowing to the oceans (Oki and Kenae, 2006; Bengough, 2012).

Mekonnen and Hoekstra (2011) recently performed an exhaustive country-by-country, crop-by-crop assessment of the green and blue water footprints of croplands, afterward comparing their detailed results with a half dozen similar but perhaps less complete earlier tallies of the consumptive use of water by crops. Their data, which sharpen, but do not change, the implications of previous work, reveal the very important fact that nearly 90% of the water consumed by croplands worldwide is green water. Even irrigated croplands have a green water footprint that is actually larger than their blue water footprint (Rost et al., 2008; Mekonnen and Hoekstra, 2011). The immediate implication, as noted by Rockström et al. (2009a) and emphasized by Mekonnen and Hoekstra (2011), is that an evident opportunity exists to meet the global food demand developing over the next 40 yr by optimizing green water use on extant croplands without further over-taxing either the land or the blue water resources of the world.

♦ Framing the Challenge: Strategy

Under the three constraints discussed above, the challenge confronting vadose zone research in optimizing the use of green water resources for crop production can be formulated succinctly in terms of two hydrologic master variables, “green water availability” and “productive green water flow,” which emerge as determinants of maximal crop yield in a model based on the positive correlation between crop yield and transpiration (Rockström and Falkenmark, 2000; Falkenmark and Rockström, 2004):

The challenge to vadose zone research is to increase both green water availability and productive flow in croplands.

“Green water availability” is the percentage of the nominal transpiration requirement for maximal yield of a crop that is actually available during the growing period. Evidently the upper limit of this quantity is equal to 100 times the ratio of precipitation to the transpiration requirement (both expressed in the same units), whereas its lower limit is the green water content below which crop failure is certain, with this lower limit also expressed as a percentage of the transpiration requirement (Rockström and Falkenmark, 2000). Green water availability is thus dependent intrinsically on both weather and climate, as well as on crop characteristics and soil hydrologic behavior. The second of the two variables, “productive green water flow,” is equal to 100 times the ratio of crop transpiration to cropland evapotranspiration (Rockström and Falkenmark, 2000). The percentage of green water flow that is productive will thus depend intrinsically on characteristics of the crop grown and on the efficacy of its rhizosphere in promoting transpiration over evaporation.

Rockström et al. (2007) illustrate the strategy involving these two master variables through an example typical of rainfed maize (*Zea mays* L.) grown in the semiarid regions of Sub-Saharan Africa (Fig. 1). Under average conditions, the green water availability is about 40% due to precipitation losses from runoff and deep percolation, while

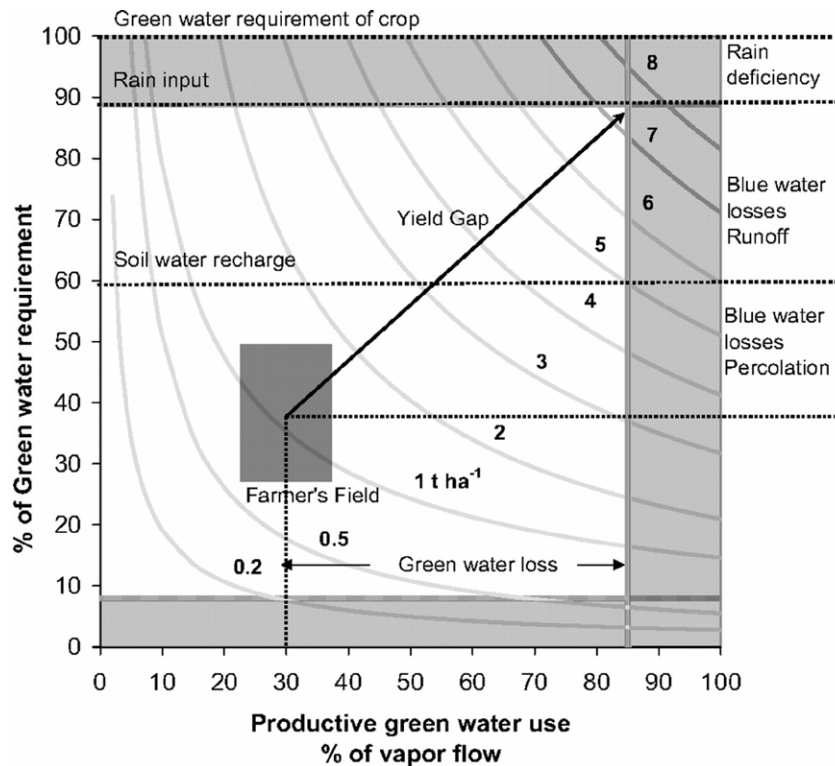


Fig. 1. Maize (*Zea mays* L.) yield isopleths (tonnes per hectare) as a function of green water availability (y -axis) and the productive flow of green water (x -axis). The gray rectangle indicates the typical ranges of the two independent variables for semiarid regions of Sub-Saharan Africa, with an average yield of 1 t ha^{-1} . See text for additional details. Reprinted with permission from Rockström, J., M. Lannerstad, and M. Falkenmark. 2007. Assessing the water challenge of a new green revolution in developing countries. PNAS 104:6253–6260. Copyright 2007 National Academy of Sciences, United States.

about 30% of the total green water flow is transpired, leading to an average maize yield of 1 t ha^{-1} , which is quite low by comparison to other developing areas of the world. However, given the same green water availability, if 85% of the green water flow were to become productive, the yield could triple. (Follow the vertical line marking 85% on the x axis in Fig. 1 up to its intersection with the dotted horizontal line marking 40% on the y axis.) Rockström et al. (2007) infer from this example that “there are no hydrological limitations to attain a doubling of yield levels” (at least with respect to maize grown in semiarid Sub-Saharan Africa), a point echoed by Foley et al. (2011) in their recent assessment of the prospects for increasing global crop yields. Instead, the limitation on maize yield in semiarid Sub-Saharan Africa appears *prima facie* to be one of plant nutrient availability (Foley et al., 2011), which, if remedied, would increase the productive flow of green water and, therefore, crop biomass (Rockström et al., 2007). Moreover, a positive feedback exists between increasing crop biomass and the productive flow of green water, in that the concomitant enlargement of the crop canopy would enhance soil shading, thus decreasing soil evaporation (Falkenmark and Rockström, 2004).

These same points were made by Sánchez (2010), who then tested his predictions through the Millennium Villages Project (Sánchez et al., 2007, 2009). Nziguheba et al. (2010) have reviewed the development of this project while surveying its first few years of field results. After

N–P–K fertilizer interventions to increase soil nutrient capital, maize yields were more than doubled across the project sites, reaching an average 4.4 t ha^{-1} , up from an average of 1.2 t ha^{-1} and well above the project goal of 3.0 t ha^{-1} (Nziguheba et al., 2010). As noted by Sánchez et al. (2009), these encouraging results reflect the expected increase in the productive flow of green water associated with larger crop biomass as well as the synergistic crop canopy effect noted above: “At current African yields, about two-thirds of soil moisture is lost via soil evaporation, leaving only one-third of the captured rainfall available for plants. But when cereal yields rise from 1 to 3 t ha^{-1} , the crop canopy closes and the balance flips over: only about a third is lost by soil evaporation, and two-thirds is funneled through the plants as transpiration.”

Addressing Complexity: Plant–Soil Feedback

The crop canopy feedback effect observed in the Millennium Villages Project is a simple example of what is termed in terrestrial ecology as a “plant–soil feedback” (Ehrenfeld et al., 2005; Bardgett and Wardle, 2010). Increasing the soil nutrient capital resulted in an increase in transpiration and, therefore, crop canopy size, which through shading effects caused a “vapor shift,” i.e., a decrease in soil evaporation in favor of increasing transpiration (Falkenmark and Rockström,

2004). The output of the transpiration process, crop biomass production, induced a feedback, soil shading, that amplified the input of the transpiration process, productive green water flow, which then increased crop biomass production. More generally, a plant–soil feedback is a change in soil conditions (the input) induced by plants (the output), with this induced change in soil conditions then leading to some further change in the plants. Plant–soil feedbacks can affect either the biotic or the abiotic properties of soil, as well as its biological, chemical, or physical processes (Ehrenfeld et al., 2005).

In the maize canopy example, the plant–soil feedback was deemed positive because it increased the productive flow of green water. Another evident feedback resulting from soil nutrient capital is creation of a rhizosphere. This change in soil properties by plants can encourage the emergence of root parasites and soil pathogens, leading to a decrease in plant biomass and, therefore, a negative plant–soil feedback, one that has been commonly identified in terrestrial ecosystems undergoing secondary succession (Kulmatiski et al., 2008, 2012; Bardgett and Wardle, 2010). On the other hand, if creating a rhizosphere promotes a mutualistic relationship between plant roots and soil microorganisms that enhances biomass production, the plant–soil feedback would be judged positive (Bardgett and Wardle, 2010; Schnitzer et al., 2011). Such considerations quite naturally highlight the importance of both the rhizosphere and the soil microbiome, the community of microorganisms, especially bacteria and fungi, that inhabit soil ecosystems (Wardle et al., 2004; Bardgett and Wardle, 2010; Wall et al., 2012). These communities are major contributors to global biodiversity while catalyzing many soil physicochemical processes, particularly those occurring in the rhizosphere (Wardle et al. 2004; Bardgett and Wardle 2010). And it is through the rhizosphere that all productive green water flows—currently 40% of all freshwater flows in the world—must pass.

Studies of plant–soil feedbacks are an emerging subdiscipline of terrestrial ecology (Ehrenfeld et al., 2005; Kulmatiski et al., 2008, 2012; Brinkman et al., 2010; Bardgett and Wardle, 2010; Bardgett, 2011; Wall et al., 2012; van der Putten et al., 2013). However, they are saddled with a daunting complexity arising from the intricacies of root architecture (Pierret et al., 2007) and the high biodiversity of the soil microbiome, with a multitude of interactions possible among its thousands of species and between those species and plant roots (Bardgett and Wardle, 2010; Kristin and Miranda, 2013). Intriguing for future research on croplands, Kulmatiski et al. (2012) recently suggested on the basis of a comprehensive new model that, for a plant species to thrive in monoculture, plant–soil feedbacks must necessarily be positive. As noted in a thought-provoking review by Bakker et al. (2012), plant–soil feedbacks are selective pressures that drive the evolution of the soil microbiome and, therefore, “enhancing our ability to manipulate or direct these [selective pressures] could offer progress toward sustainability through development of crop varieties that selectively enhance beneficial functions within the soil microbiome.”

Do plant–soil feedbacks exist that would directly impact green water availability and productive green water flow? Plant roots interact with the rhizosphere in a multiplicity of ways (Pierret et al., 2007; Bengough, 2012; Kristin and Miranda, 2013), one of them being to exude complex mixtures of organic compounds (Bakker et al., 2012), particularly the polysaccharide-rich material, mucilage. One result of this plant–soil feedback, besides the direct stimulation of the soil microbiome (Bakker et al., 2012; Kristin and Miranda, 2013), is to increase the water-holding capacity of soil under unsaturated conditions (Carminati et al., 2010, 2011). This change, in turn, implies an increase in green water availability. Evidence also exists that mucilage can cause the rhizosphere to have different hydraulic properties from nonrhizosphere soil (Carminati et al., 2011). The overall impact on green water from these two feedback effects appears to be that “the rhizosphere acts as a buffer that softens the hydraulic stress experienced by roots in soils, and favors water availability to roots during drought” (Carminati et al., 2010). Indeed, Marasco et al. (2012) report that the soil microbiome which evolved in the rhizosphere of an important crop plant, pepper, under desert farming conditions significantly promoted plant growth under drought stress. Encouraging claims such as these are currently being examined as part of a recent surge in the ability to resolve small-scale details of rhizosphere structure and behavior during water uptake by plant roots (Moradi et al., 2011; Zarebanadkouki et al., 2012) and the development of more sophisticated models of root water uptake (de Willigen et al., 2012; Carminati, 2012). This biophysical research, however, must be complemented by collaborative biogeochemical and microbiological studies of the rhizosphere during green water redistribution and productive flow.

Knowing that cropland expansion and increasing withdrawals of blue water for irrigation are not likely to be the dominant options for meeting future demands on global food production places useful constraints on what priorities should obtain for developing water management strategies (Rost et al., 2009; Rockström et al., 2009a, 2012; Mitchell et al., 2012) as well as the required vadose zone science. Knowing further that a major goal is to optimize the availability and productive flow of green water not only helps to focus research priorities, but also highlights the importance of developing new methodologies that transcend both disciplinary boundaries and the contrasts that exist among the principal food crops and the soils they are grown in across the planet. But the grand scientific challenge offered by crop intensification cannot be met in the absence of a holistic understanding of the properties of soils that Virgil praises in the mellifluous poem which opened this paper.

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