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Global potential to increase crop production through water management in rainfed agriculture

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Abstract

This modeling study explores—spatially explicitly, for current and projected future climate, and for different management intensity levels—the potential for increasing global crop production through on-farm water management strategies: (a) reducing soil evaporation (‘vapor shift’) and (b) collecting runoff on cropland and using it during dry spells (‘runoff harvesting’). A moderate scenario, implying both a 25% reduction in evaporation and a 25% collection of runoff, suggests that global crop production can be increased by 19%, which is comparable with the effect of current irrigation (17%). Climate change alone (three climate models, SRES A2r emissions and population, constant land use) will reduce global crop production by 9% by 2050, which could be buffered by a vapor shift level of 50% or a water harvesting level of 25%. Even if realization of the beneficial effects of rising atmospheric CO_2 concentration upon plants was ensured (by fertilizer use) in tandem with the above moderate water management scenario, the water available on current cropland will not meet the requirements of a world population of 9–10 billion.

Keywords: food security, vapor shift, water harvesting, climate change, agriculture, water resources

1. Introduction

On average, 1300 cubic meters per capita per year (m^3 cap^{-1} yr^{-1}) of fresh water are required to produce the food for a healthy diet of 3000 kcal cap^{-1} day^{-1} with a 20% meat share (Rockström *et al* 2007). This means that $>$8000 km^3 yr^{-1} of water are consumed (i.e. evapotranspired on rainfed and irrigated land) to feed the current world population (Rost *et al* 2008), and that an additional c. 5000 km^3 yr^{-1} will be required if the population rises to 10 billion in 2050 as suggested by the IPCC's SRES A2r scenario (Grübler *et al* 2007). A further increase in agricultural water requirements can be expected due to rising incomes and dietary changes towards more meat consumption (Liu *et al* 2008). Global climate change, elevated atmospheric CO_2 concentration, and altered incidence of pests, diseases and weeds will also noticeably impact future global food production (Easterling *et al* 2007). Whereas rising temperatures and regional soil moisture declines tend to negatively affect crop production (Parry *et al* 2004, Lobell and Field 2007, Battisti and Naylor 2009), direct effects of elevated CO_2 upon plants will probably increase production (Tubiello and Ewert 2002, Challinor and Wheeler 2008), albeit the magnitude of this effect is debatable (Long *et al* 2006, Tubiello *et al* 2007).

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The availability of fresh water and arable land are approaching their limits. Already about 15 million km^2 of the land surface is covered by cropland (Ramankutty *et al* 2008), and about 16% of this area is equipped for irrigation (Siebert *et al* 2005). During the last century, the rate of increase in 'blue' water withdrawals (from rivers, lakes, and aquifers) for irrigation and other purposes was higher than the growth rate of the world population (Shiklomanov 1998). A crucial question is to what extent cropland will have to be expanded in the future to guarantee sufficient food production for the growing world population, and to what extent the additional land and water requirements can be minimized through better management of existing cropland.

In an optimistic scenario, cropped area will increase by 9% and agricultural water withdrawals by 13% by the year 2050 (Molden 2007), which due to assumed increases in water use efficiency is notably lower than the highest expected increase in population by 67% by that time (SRES A2r). Nonetheless, a higher efficiency of blue water use or an expansion of irrigated areas is most likely insufficient to fulfill future food demand and to alleviate the still existing malnutrition of at least 850 million people (FAO 2006). In this context, it has to be noted that 60–70% of the world's current crop production is rainfed, i.e. it relies on the evapotranspiration of 'green' water (precipitation stored in the soil; Falkenmark and Rockström 2004). Altogether more than 85% of water consumed in global agriculture is green (Rost *et al* 2008). Thus, increases in crop productivity are ultimately needed not only in irrigated but also in rainfed agriculture.

To meet the water and food needs of local communities, a new agricultural revolution has been proposed (IAASTD 2008). The plea is for fundamental changes in farming away from industrial, energy-intensive agriculture that strongly depends on synthetic fertilizers and pesticides toward small-scale and agro-ecological farming including low-cost water management options and indigenous methods. From a hydrological perspective there may indeed be enough rainfall to significantly increase yields even in semiarid regions without large-scale irrigation (Rockström *et al* 2007). Many of the low yields can be explained by the processes of unproductive soil evaporation, interception losses, deep percolation and surface runoff, which amount to losses of up to 70–85% of rainfall (Rockström 2000). Despite the success of a variety of soil and water management strategies to optimize the use of rainwater for crops in demonstration plots, there is still no widespread adoption of these methods (Pandey *et al* 2003, Faures and Santini 2008). We note the high number of irrigation tanks in regions such as southern India (Gunnell and Krishnamurthy 2003), but here we focus on rainfed cropland while assuming such tanks to be at least partially installed in irrigated areas and their contribution to be covered in our irrigation simulations. Using an optimistic scenario of water availability and management in which a theoretical maximum of 85% of total evapotranspiration from cropland and pasture was assumed to be available for plant transpiration and thus biomass production, Rockström *et al* (2009) suggested that without such improvements in water productivity, a horizontal cropland expansion by about 1000 Mha would be required to produce the food for >10 billion people. This renders water management in rainfed agriculture a very important strategy to increase food production globally (Molden 2007), but the large-scale potential of these methods has not yet been quantified systematically.

While only a few field experiments have investigated local successes with these techniques, ecohydrological models can contribute significantly to understand their potential at larger scales (Kahinda *et al* 2007) and help identify suitable management options (Prinz *et al* 1998, Mbilinyi *et al* 2007). The present study is the first to quantify at a global scale yet geographically explicitly the present water limitation of crop production and the potentials of the above water management strategies for improving crop production. Analysis is based on simulations with the LPJmL dynamic global vegetation and water balance model (Bondeau *et al* 2007, Rost *et al* 2008), in which we represented several management strategies (reducing soil evaporation to achieve a vapor shift, and harvesting runoff for use during dry spells; see section 2).

2. Methods

2.1. Model and data

The LPJmL model computes the growth and productivity of natural and agricultural vegetation coupled with biogeochemical and water fluxes on 0.5° spatial and daily temporal resolution (Bondeau *et al* 2007). Key ecosystem processes such as photosynthesis, respiration, carbon allocation, evapotranspiration and its individual components, soil moisture, and drought stress are simulated in a process-based way so that they respond dynamically to climatic variations. The model considers 9 natural plant functional types and 12 crop functional types (CFTs, either irrigated or rainfed, corresponding to the world's most important field crops: temperate/tropical cereals, temperate/tropical roots, rice, maize, pulses, sunflower, soybean, groundnuts, rapeseed, and pasture).

The annual fractions of cropland and pasture per grid cell were prescribed for the years 1901–1992 using the datasets by Ramankutty and Foley (1999) and Klein Goldewijk and Battjes (1997); for the period up to the year 2000 the coverage was assumed to follow the trend of the preceding 20 years. Future land use and irrigation areas were held constant at the values of 2000. The distribution of CFTs within a grid cell was taken for the year 1990 from Leff *et al* (2004) and interpolated backwards and forwards assuming constant relative proportions. Irrigation was assumed to occur on the fractions of a grid cell equipped for irrigation (Siebert *et al* 2007). Irrigation water requirements were derived from the soil water deficit and from country-specific irrigation efficiencies that result from differences in dominant irrigation types among countries. We assumed that these gross requirements can always be met (Rost *et al* 2008). The growing seasons of the CFTs were simulated to be initiated by a sowing date dependent on temperature or precipitation and to end with harvest when maturity is reached. The intensity of present agricultural management is represented by assuming the CFT's maximum leaf area index to be higher in intensively

Table 1. Overview of the different water management simulations.

Present climate 1971–2000		
(a)	OPT	Maximum NPP* under always saturated soil
(b)	BAS	Baseline run including irrigation
(c)	INO	BAS, but no irrigation
(d)	VS	BAS with reductions in E_S of 10, 25, 50, and 85%
(e)	RH	BAS with runoff harvesting of 10, 25, 50, and 85%
(f)	VS + RH	Same-level intensity combinations of VS and RH
Projected future climate 2041–2070		
(a)–(f)	CC	Climate change under constant year 2000 CO_2 concentration
(a)–(f)	CC + CO_2	Climate and CO_2 change

managed regions, as derived from data on fertilizer input (Bondeau *et al* 2007). We assume that management intensity will not change in the future. LPJmL is validated against biogeochemical and hydrological observations including crop yields, river discharge, soil moisture, and rainfed and irrigated water consumption (Gerten *et al* 2004, Bondeau *et al* 2007, Rost *et al* 2008, Biemans *et al* 2009).

2.2. Simulation of water fluxes and water limitation to crop production

Soil water content W is updated daily for each CFT within each grid cell, following the balance between the amount of infiltrated water (precipitation P, snowmelt M, and irrigation water 'Irr' minus interception loss from leaves E_I) and that removed from the soil through surface and subsurface runoff R (generated from excess water above field capacity), soil evaporation E_S, and plant transpiration E_T (all in mm day^{-1}) (Gerten *et al* 2004):

$$W = (P + M + \mathrm{Irr} - E_I) - R - (E_S + E_T). \qquad (1)$$

E_S depends on potential evapotranspiration determined by the Priestley–Taylor method (E_{pot} times the Priestley–Taylor coefficient $\alpha = 1.32$) and the relative moisture in the top 20 cm of the soil W_{r20}. It is computed for the fractions of bare soil of cropland as given by the coverage with vegetation f_v and the daily status of crop-specific leaf phenology 'phen':

$$E_S = E_{pot} \alpha W_{r20}^2 (1 - f_v \mathrm{phen}). \qquad (2)$$

Crop transpiration E_T is determined for each CFT as the minimum of atmospheric demand D and water supply S:

$$E_T = \min(S, D) \qquad (3)$$

S is regulated by soil moisture and plant hydraulic traits; when the soil is saturated, E_T reaches a maximum E_{max} (5–8 mm day^{-1}) and declines linearly with W weighted by the CFT-specific fraction of roots in each soil layer. D (mm day^{-1}) is a function of E_{pot} times a maximum Priestley–Taylor coefficient ($\alpha_m = 1.391$) and the potential, water-unlimited canopy conductance g_{pot} (mm s^{-1}):

$$D = \frac{(1 - f_{wet}) E_{pot} \alpha_m}{1 + g_m / g_{pot}} \qquad (4)$$

where f_{wet} is the fraction of the day that the canopy is wet, and g_m is a scaling coefficient (3.26 mm s^{-1}). g_{pot} is calculated from the photosynthesis rate and ambient CO_2 concentration (details in Gerten *et al* 2007). E_I is determined as:

$$E_I = \min(\mathrm{LAI}\, i\, \mathrm{phen},\ P + \mathrm{Irr},\ E_{pot}) f_v \qquad (5)$$

where LAI is the leaf area index and i a factor accounting for vegetation type and rainfall regime.

Total evapotranspiration E, i.e. crop water consumption, is computed as the sum of E_T, E_S and E_I. Net primary production NPP (Gt dry matter) is defined as gross primary production less autotrophic respiration. The former is estimated daily from the fractional coverage of a CFT in a grid cell, leaf phenology and weather conditions. The latter is the compound of maintenance respiration (calculated based on the size of the living tissue pools, their assigned C:N ratios and weather data) and growth respiration (the cost of producing new tissues, calculated as a fraction of NPP) (Sitch *et al* 2003). The degree of water limitation of crop production was computed as the ratio between NPP and the production that could theoretically be reached if E_T was always at its maximum (NPP*). The CO_2 effect upon E_S and NPP includes both physiological and structural vegetation responses (Gerten *et al* 2007).

2.3. Water management scenarios

Several simulations were performed to estimate crop NPP under different conditions (table 1):

(a) OPT: a model run in which the theoretical NPP* was simulated by assuming an always saturated soil ($S = E_{max}$).
(b) BAS: the baseline run, in which crops on areas equipped for irrigation were assumed to be irrigated, thus representing irrigation as the only water management (which reflects the present situation for most regions of the world).
(c) INO: a simulation in which no irrigation was assumed.
(d) VS: model runs (based on BAS) that emulate a vapor shift from non-productive evaporation to productive transpiration by systematically reducing year-round E_S (equation (2)) by, respectively, 10, 25, 50, and 85% (VS10, VS25, VS50, and VS85 simulations). In practice, such a vapor shift—an increase of the E_T:E ratio—can be

attained, for example, through soil and water conservation strategies like mulching or different tillage systems. Field studies showed that E_S can be reduced by 34–50% in this way (Sauer *et al* 1996); in semiarid regions, a maximum E_T:E ratio of 85% appears to be feasible (Rockström and Falkenmark 2000).

(e) RH: model runs (based on BAS) that emulate rainwater harvesting strategies by concentrating and storing, respectively, 10, 25, 50, and 85% of R on cropland over a year (e.g. in dikes, ponds, sand, or subsurface dams; Rockström 2000) and by redirecting this water to crops in periods of water stress so as to fulfill supplemental irrigation water requirements on rainfed cropland (RH10, RH25, RH50, and RH85 simulations). By these methods the risk of dry spells is reduced and the resilience of rainfed agricultural systems improved (Barron *et al* 2003). For dry areas it was shown that water harvesting systems recover otherwise lost water by up to 50% (e.g. Oweis and Hachum 2006).

(f) Both management strategies combined for equivalent levels of management intensity (VS10 + RH10, VS25 + RH25, VS50 + RH50 and VS85 + RH85).

(g) CC: model runs (a)–(f) under transient climate change (see below) with CO_2 being held constant at the year 2000 value.

(h) CC + CO_2: Same as (g) but with increasing CO_2 concentration.

We analyzed the differences between these model runs to estimate the effect on NPP of irrigation (INO minus BAS), and of the different management options (VS, RH, and VS + RH minus BAS) for the present, under SRES-A2 climate change (CC), and under climate change with CO_2 increase (CC + CO_2), respectively. Estimates for the future were represented as averages of the results under three climate scenarios (see below). We also used the spatial distribution of the revised high population growth scenario A2r for the year 2050 (Grübler *et al* 2007) to relate the effects of the water management options to global food demand. Since the A2r population scenario is at the upper end of the SRES range (10.2 billion in 2050) and because food and water demand are strongly affected by the population number, we also analyzed results for medium (B2) and low fertility (B1) population scenarios that show, respectively, a world population of 9.4 and 8.7 billion in 2050. To reduce the number of simulations, we did not compute the climate change impacts under B1 and B2 emissions. We expect the adverse effects of climate change (NPP reductions) reported below to be less severe in these scenarios, but at the same time the beneficial effects of rising CO_2 concentration would also be less pronounced.

2.4. Computation of water requirements for crop production

To estimate the effect of the water management options on securing global crop production, we followed the approach of Rockström *et al* (2007), assuming that as a global average 1300 m^3 cap^{-1} yr^{-1} of blue and green water are required under present conditions to produce 3000 kcal cap^{-1} day^{-1} for a healthy diet (20% meat share). Actually, however, this water requirement differs among regions. To roughly account for these differences, we distributed the global average among countries according to their water productivity (i.e. the water consumed per unit of NPP), such that regions with low water productivity got values higher than 1300 m^3 cap^{-1} yr^{-1} (e.g. around 2000 m^3 cap^{-1} yr^{-1} in many countries of sub-Saharan Africa), and vice versa. (Note that these values refer to the normative goal of a diet of 3000 kcal; for producing today's actual diets, water requirements are significantly lower in many regions of the South.) Countries in which the water availability per capita falls below the thus computed value are regarded as water-stressed. Analogously, the water stress threshold changes under each of the scenarios computed here, following the individual changes in NPP and E and, thus, water productivity.

2.5. Model setup

LPJmL was driven by an updated version of the CRU TS2.1 climate dataset (0.5° spatial resolution) of monthly air temperatures, precipitation, and cloud cover (Österle *et al* 2003) for the period 1901–2000, preceded by a 1000 yr spinup during which the climate of 1901–1930 was repeated. CO_2 concentrations were as in Rost *et al* (2008). For the simulations under future climate, starting from the same equilibrium, the model was driven by the output from three different climate models (HadCM3, ECHAM5/MPI-OM, and CCSM3 (Randall *et al* 2007) disaggregated to 0.5° resolution and normalized to observed climate for 1961–1990) under the A2 emissions trajectory for the period 1901–2070. Sub-monthly weather variability was derived by statistical procedures (Gerten *et al* 2004). All results were computed at daily time steps for each CFT separately, but are presented as annual averages over all CFTs for 1971–2000 and 2041–2070, respectively.

3. Results and discussion

3.1. Present water limitation of crop production

We estimated a maximum achievable global crop NPP* of 23.5 Gt in the absence of water limitation (OPT simulation). Only about half of this theoretical potential would be realized without any irrigation (11.4 Gt INO simulation; table 2). This reflects the fact that NPP is strongly water-limited in many regions of the world (figures 1 and 2), and suggests a high potential for increasing NPP through proper management of blue and green water in water-scarce regions. In contrast, in tropical, marine west coast, humid subtropical, and subarctic climate zones NPP (INO) is already close to NPP* (OPT; figure 1), which implies low potentials for increasing NPP. Thus, as confirmed by earlier studies (Gregory *et al* 2000, Hatfield *et al* 2001, Pandey *et al* 2003), the likely success of soil and/or water management differs among regions, mainly due to differences in climate.

Through present irrigation, an increase in global crop NPP by 17% up to 13.3 Gt is already achieved (INO versus BAS; table 2), mainly in regions with large areas equipped for irrigation (figure 3(a)). On irrigated land, crop NPP would be lower globally by 69% without irrigation, i.e. green

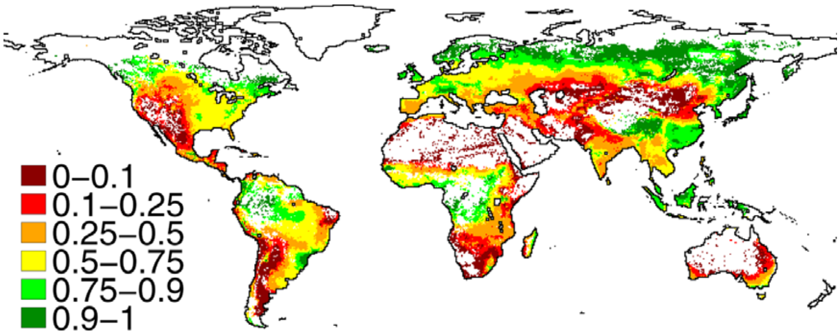

Figure 1. Water limitation of crop production in the absence of irrigation, i.e. ratio of NPP (INO simulation) and NPP* (OPT simulation), 1971–2000 averages. The lower the ratio the stronger the water limitation.

Table 2. Simulated global NPP (Gt) presented as 1971–2000 averages for the present and as 2041–2070 averages for CC and CC + CO_2 (mean values of three climate models).

	INO	BAS	VS				RH				VS + RH			
			10	25	50	85	10	25	50	85	10	25	50	85
Present	11.4	13.35	13.66	14.15	15.08	16.64	13.91	14.87	16.16	17.44	14.27	15.85	18.12	20.4
CC	10.19	12.18	12.43	12.85	13.63	14.99	12.63	13.41	14.6	15.98	13	14.46	16.57	18.7
CC + CO_2	14.69	17.02	17.28	17.68	18.43	19.7	17.46	18.22	19.35	20.62	17.8	19.19	21.23	23.36

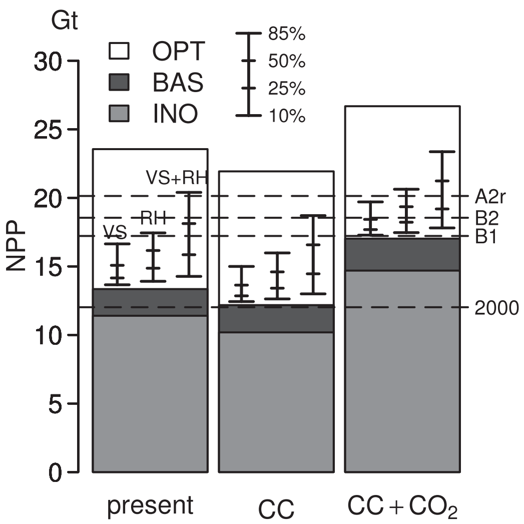

Figure 2. Crop NPP (Gt) for the different simulations under present climate (1971–2000 averages), under future climate change (CC), and under both climate and CO_2 change (CC + CO_2) (2041–2070 averages of three climate models, A2 emission scenario). Horizontal lines indicate NPP requirements at a population of 6.1 billion in 2000 and the estimated requirements for different population scenarios (SRES B1, B2, A2r).

water contributes about a third to crop production there. Comparable estimates were found by Siebert and Döll (2009) who suggested a decrease in crop production by 17.8% and on irrigated land by 54% in the absence of irrigation. Previous estimates of global crop NPP (rainfed and irrigated) were of the order of 12 Gt (Rojstaczer *et al* 2001, Monfreda *et al* 2008). Our slightly higher estimate of 13.3 Gt might be explained by the larger area of agricultural land according to Ramankutty and Foley (1999) used in our study, and by our assumption of optimum irrigation on equipped areas.

3.2. Potential of water management strategies under present climate

The potential to increase global crop NPP by reducing soil evaporation is estimated to be 0.31 Gt (2.3%) under low (VS10) and 3.3 Gt (24.7%) under intense (VS85) vapor shift management (figure 2, table 2). The VS25 simulation suggests a high potential (>20%) mainly in semiarid regions such as the midwestern United States, parts of South America, the Sahel, southern Africa, Central Asia, and south-eastern Australia (figure 3(b)). Even on irrigated areas, vapor shift management can reduce water requirements by 5% (147 km^3 yr^{-1}) under low (VS10) and by 83% (1499 km^3 yr^{-1}) under intense management (VS85) (data not shown). Together with improvements in irrigation efficiency not studied here—which may, together with expansions of irrigated areas, amount to about 800 km^3 yr^{-1} globally (Falkenmark and Rockström 2004)—the thus saved blue water could be used for purposes other than agriculture, or for expanding irrigated areas to currently rainfed cropland.

Runoff harvesting was simulated to increase global NPP by 0.57 Gt (4.2%) under low (RH10) and by 4.1 Gt (30.7%) under high storage (RH85) (figure 2, table 2). In the RH25 simulation tropical wet and dry regions like Central America, parts of Brazil, eastern and southern Africa in particular show large potentials (>20%) for increasing NPP (figure 3(c)). These magnitudes are comparable to those in Wisser *et al* (2009), who found that overall cereal production in low-yield regions could be increased by about 15% for a medium variant of small reservoir construction, with highest potentials in Africa and Asia.

Regional differences in the potential to increase NPP between the VS and RH scenario can be explained primarily by climatic differences. Whereas vapor shift management seems to be more efficient in dry regions with low R, runoff

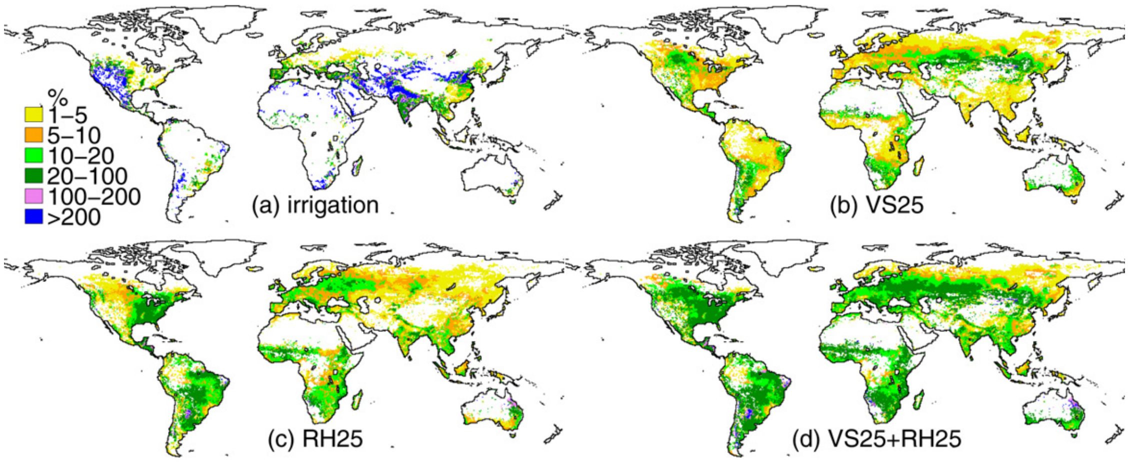

Figure 3. Percentage increase in NPP (1971–2000 averages) through (a) irrigation (BAS-INO), (b) vapor shift of 25% (VS25-BAS), (c) water harvesting of 25% (RH25-BAS), and (d) the combination of (b) and (c) (VS25 + RH25-BAS).

harvesting was found to be more effective if substantial amounts of *R* can be stored outside of the growing period. In addition, crop management practices depend strongly on soil texture, with improvements in crop production being most promising on soils with high water holding capacity (Gregory *et al* 2000, Ngigi 2003).

The combination of both management strategies (VS + RH) results in an increase in NPP by 0.92 Gt (6.9%) in VS10 + RH10 and by 7.05 Gt (52.8%) in VS85 + RH85 (figure 2, table 2). Pronounced increases in NPP can be achieved mainly in regions where present NPP reaches less than 10% of NPP* (figures 1 and 3(d)), which agrees well with recent findings by Faures and Santini (2008) for sub-Saharan Africa.

The aim of this study is to demonstrate the range of NPP increases given different levels of water management intensity without deeming a particular scenario to be most realistic. Nonetheless, we think that a global implementation of the 85% scenario is clearly unrealistic (though physically possible), and even the 50% scenario is very ambitious, while the 25% scenarios seem to be a possible option: Falkenmark and Rockström (2004) suggested an improvement of green water productivity by 1530 km^3 yr^{-1} through a combination of various techniques, which is comparable to our estimates of a water saving of about 1650 km^3 yr^{-1} and an associated NPP increase of 2.5 Gt in the V25 + RH25 scenario. The actual potentials and mixtures of VS and RH methods will certainly differ between regions and require investigation in dedicated regional studies. Note that we did not account for evaporation losses of harvested water nor for the possibility that water harvesting reduces blue water availability in downstream locations, which may lead to lower overall water savings within river basins and globally, especially in the scenarios of high-level management (see also Wisser *et al* (2009)).

3.3. Future potential of water management under climate change only

The effect of climate change only (CC) is a decrease in NPP*, and in NPP under all water management simulations, compared to the present situation (decrease by 9% in BAS by 2050, figure 2). This is due primarily to regional precipitation declines and generally higher temperatures that lead to higher crop water limitation and more direct crop damage. Similar results were found by Parry *et al* (2004), who estimated a climate change-driven decrease in global crop production of 10% by 2080. Under climate change only, irrigation on areas currently equipped for irrigation would increase the otherwise rather low crop production by 19.5% from 10.2 to 12.2 Gt (figure 2, table 2), i.e. future irrigation will continue to play an important role on present land equipped for irrigation.

The potential to increase NPP by the other water management strategies ranges from 0.26 Gt (2%) in VS10 to 3.9 Gt (32%) in RH85, and from 0.82 Gt (7%) in VS10 + RH10 to 6.5 Gt (54%) in VS85 + RS85 (figure 2, table 2). The absolute rise in crop production that can be attained was found to be slightly lower under future climate than at present, due to globally lower amounts of water stored in the soil and/or harvestable (data not shown). The relative potential to upgrade NPP by water management, however, is of a similar magnitude under future climate change as at present.

Note that either a vapor shift of about 50% or a water harvesting level of 25% would have to be achieved if the adverse consequences of global climate change were to be counterbalanced, i.e. if the current crop production levels were to be held. However, crop production will have to be increased significantly in the future, with the actual amount of this increase depending on population development (figure 2).

3.4. Future potential of water management under climate and CO_2 change

Other than under CC, the global joint effect of climate and CO_2 change ($CC + CO_2$) is an increase in NPP* and NPP, respectively (figure 2). The isolated effect of rising CO_2 concentration is an increase in global crop NPP by 28% by the 2050s, which is somewhat higher than suggested by forest FACE experiments (about 23% at a CO_2 level of about 500 ppm; Norby *et al* 2005). Irrigation was simulated to increase

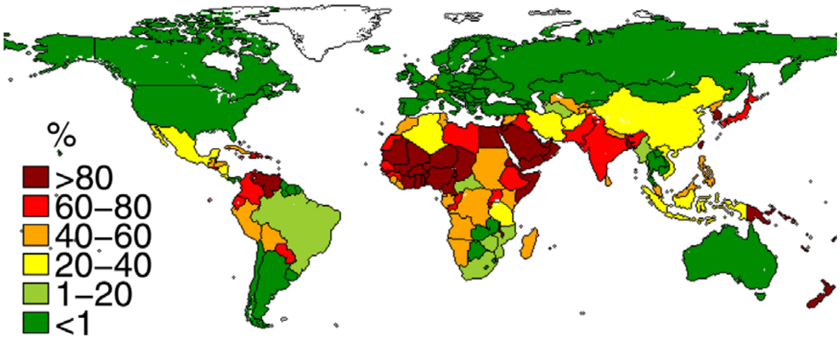

Figure 4. Percentage of country population that will be water-stressed in the future, given population (A2r scenario for 2050), climate and CO_2 change (A2, three climate models; 2041–2070 averages) and assuming that the VS25 + RH25 water management scenario is realized.

NPP by 16% to 17 Gt. The potential to increase NPP by the diverse water management options ranges from 0.26 Gt (1.5%) in VS10 to 3.7 Gt (22%) in RH85, and from 0.78 Gt (5%) in VS10 + RH10 to 6.3 Gt (37%) in VS85 + RH85 (figure 2, table 2).

It is noteworthy that the CO_2 effect more than offsets the global NPP decrease induced by climate change (figure 2), as was also shown elsewhere (Tubiello and Ewert 2002, Gerten *et al* 2007, Challinor and Wheeler 2008). At any rate, the beneficial CO_2 effect should be interpreted as a maximum effect, the realization of which represents a major challenge due to the complex interactions between photosynthesis and yields, and limitations to crop growth through low nutrient availability, soil degradation, pests, weeds, and diseases (Ainsworth *et al* 2008). These co-limitations, and especially N and P limitations, are not explicitly considered in our model, but, as Hickler *et al* (2008) concludes, current observational evidence suggests that the projected strong impacts of increasing CO_2 on NPP are realistic if other limitations are absent. Please also note that we assumed the present management intensity to remain constant in the future, meaning that absolute NPP may be higher (or lower) in the non-CO_2 case. In this context we recognize that the computed E_T:E ratio—which is influenced by management and which, in turn, influences the outcome of the VS simulations in particular—depends on the daily phenological status of the CFTs. Preliminary studies based on more recent land use data and a refined parameterization of agricultural management show, however, that the present results are still valid (Fader *et al* 2009).

3.5. Implications for food self-sufficiency

As a measure of a country's food self-sufficiency, we calculated the number of people that will be water-stressed by 2050 (see section 2.4 for computation of this water stress), exemplary for the A2 scenario and under consideration of a successfully implemented VS25 + RH25 scenario (figure 4). Under these conditions, water availability will still be sufficient to fulfill the food demand in most developed and water-rich countries. In contrast, future food self-sufficiency remains unachievable for many countries especially in North Africa, the Middle East and South Asia, such that the global number of people living in countries without enough blue and green water (on present cropland) for producing a healthy diet increases from the present 2.3 billion to about 6 billion by the 2050s (data not shown). The associated additional water demand would be about 4500 $km^3\ yr^{-1}$ (Gerten and Rost 2009).

Import of agricultural products and the embedded virtual water eases countries' water shortages (Chapagain *et al* 2006). However, even if the above assumption of self-sufficiency was discarded by assuming that virtual water trade fully balances the regional differences in blue and green water consumption on present irrigated and rainfed cropland, a water gap of about 2800 $km^3\ yr^{-1}$ would remain at a population size of 10.2 billion (data not shown). Since water savings in irrigation probably will not be able to fill this gap (see above), continuing global expansion of cropland at a rate similar to the present rate appears to be inevitable (Rockström *et al* 2009). It is questionable, however, whether this land is actually available and what tradeoffs with other land uses will have to be made. We aim to explore these land limitations and tradeoffs in future studies, but a qualitative comparison with recent results based on our model already indicates that tough choices on land and water use will have to be made if the global demand for sustainable bioenergy production is taken into account (WBGU 2009).

The above estimates are based on the assumption that present diet composition will remain stable in the future, which is unlikely, however, given the recent trends toward increased meat consumption (which imply higher water consumption) and other prospective lifestyle changes. Also, our related assumption that 1300 $m^3\ cap^{-1}\ yr^{-1}$ of water are required for producing a healthy diet of 3000 kcal $cap^{-1}\ day^{-1}$ represents a global average, while the actual water requirements differ among regions depending, for example, on the virtual water content of individual crops. In addition, water demand crucially depends not only on lifestyle choices but also on population size, and we find that there will be future water gap even under the low fertility scenarios (figure 2; see also Brichieri-Colombi (2008)). Forthcoming analyses will have to account comprehensively for a wider range of climate, population, and lifestyle scenarios as well as for the concrete potential of virtual water trade.

4. Conclusion

This study represents the first spatially explicit quantification of water limitations in global crop production and the potential of different water management strategies to upgrade crop growth, under both present and projected future climate conditions. A key finding is that an area-wide combination of water harvesting and vapor shift techniques could increase global crop production by almost 20%. This result underscores quantitatively and scales up to a global scale previous local observations of high potentials for rising crop production and reducing risk of crop failure by proper soil and water management in rainfed agriculture (Rockström 2003, Ali and Talukder 2008, Faures and Santini 2008). But the study also indicates that even the most ambitious and large-scale water management efforts on present cropland will not be sufficient to guarantee the food demands of a growing world population. This evidence poses crucial questions about tradeoffs between future land and water use for irrigated and rainfed agriculture, natural ecosystems and bioenergy. It furthermore highlights the need for exploring and combining all options of more efficient irrigation and/or expansion of irrigated agriculture, of plant breeding and genetic development, and of more effective virtual water trade.

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