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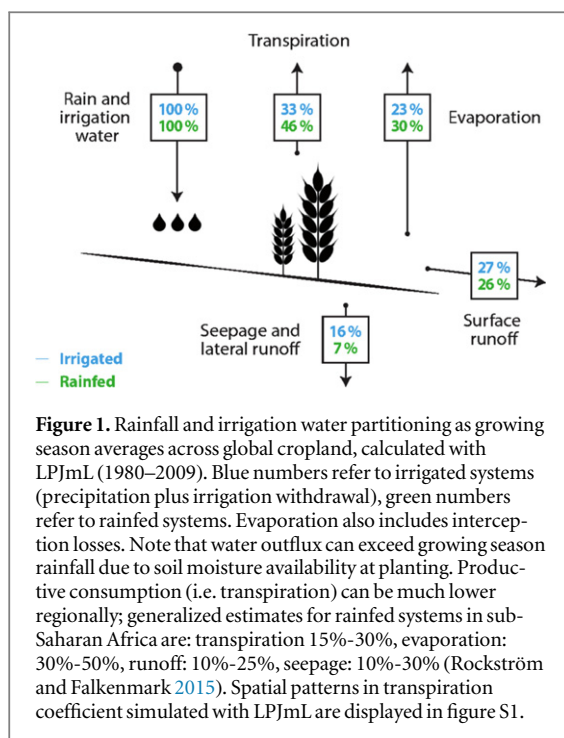
J Jägermeyr^{1,2}, D Gerten^{1,2}, S Schaphoff¹, J Heinke^{1,3,4}, W Lucht^{1,2} and J Rockström⁵¹ Research Domain Earth System Analysis, Potsdam Institute for Climate Impact Research (PIK), Telegraphenberg A62, 14473 Potsdam, Germany² Geography Department, Humboldt-Universität zu Berlin, Unter den Linden 6, 10099 Berlin, Germany³ International Livestock Research Institute (ILRI), P O Box 30709, Nairobi, 00100 Kenya⁴ Commonwealth Scientific and Industrial Research Organization (CSIRO), St. Lucia, QLD 4067, Australia⁵ Stockholm Resilience Centre, Stockholm University, Stockholm 106 91, SwedenE-mail: jonas.jaegermeyr@pik-potsdam.de**Keywords:** sustainable intensification, yield gap, water harvesting, conservation agriculture, irrigation efficiency, food security, climate change adaptationSupplementary material for this article is available [online](#)**Abstract**

As planetary boundaries are rapidly being approached, humanity has little room for additional expansion and conventional intensification of agriculture, while a growing world population further spreads the food gap. Ample evidence exists that improved on-farm water management can close water-related yield gaps to a considerable degree, but its global significance remains unclear. In this modeling study we investigate systematically to what extent integrated crop water management might contribute to closing the global food gap, constrained by the assumption that pressure on water resources and land does not increase. Using a process-based bio-/agrosphere model, we simulate the yield-increasing potential of elevated irrigation water productivity (including irrigation expansion with thus saved water) and optimized use of *in situ* precipitation water (alleviated soil evaporation, enhanced infiltration, water harvesting for supplemental irrigation) under current and projected future climate (from 20 climate models, with and without beneficial CO₂ effects). Results show that irrigation efficiency improvements can save substantial amounts of water in many river basins (globally 48% of non-productive water consumption in an ‘ambitious’ scenario), and if rerouted to irrigate neighboring rainfed systems, can boost kcal production significantly (26% global increase). Low-tech solutions for small-scale farmers on water-limited croplands show the potential to increase rainfed yields to a similar extent. In combination, the ambitious yet achievable integrated water management strategies explored in this study could increase global production by 41% and close the water-related yield gap by 62%. Unabated climate change will have adverse effects on crop yields in many regions, but improvements in water management as analyzed here can buffer such effects to a significant degree.

1. Introduction

Demand for food increases as populations grow and gain wealth, thus the world might need a 60%–100% extra kcal production by 2050 to end hunger (IAASTD 2009, Tilman *et al* 2011, Alexandratos and Bruinsma 2012, Valin *et al* 2014). However, it is becoming increasingly apparent that planetary guardrails narrow down humanity’s prospects for additional

appropriation of resources and conventional intensification of agriculture (Steffen *et al* 2015). Inevitably, competition for energy, land and water rises with growing food demand, which fuels the challenge of closing the global food gap (crop calorie requirements above domestic production and imports, now and in the future) (e.g. Godfray *et al* 2010, Foley *et al* 2011, Searchinger *et al* 2013). Climate change might exacerbate this situation by increasing water stress and



hydroclimatic variability particularly in developing countries (Porter *et al* 2014, Rosenzweig *et al* 2014).

Agriculture is the single largest user of freshwater and the most important reason why the world is transgressing planetary boundaries (Rockström and Karlberg 2010). The challenge of producing enough food becomes especially delicate, as it must be met mainly on currently cultivated land since expansion and conventional intensification of agriculture comes at major environmental costs (local to global scale factors: erosion, biodiversity loss, salinization, water pollution and eutrophication, water scarcity, greenhouse gas emissions) (Matson *et al* 1997, Foley *et al* 2005, Reynolds *et al* 2015). Furthermore, significant yield gaps exist across various farming systems, indicating a substantial scope for yield gains through mitigation of nutrient and water deficiencies (Mueller *et al* 2012, Licker *et al* 2010, Global Yield Gap Atlas 2015).

Increasing production on existing agricultural land by managing available resources more efficiently, placing less pressure on the environment and sustaining future capacities, i.e. sustainable intensification, is thus seen as an important part of a solution and high on the global policy agenda (Tilman 1999, The Royal Society 2009, Garnett *et al* 2013, World Bank 2013, Dobermann and Nelson 2015). The renewed Sustainable Development Goals now stipulate sustainable agriculture as an agreed goal among all nations (United Nations 2016), but there is little quantitative evidence of how to achieve it. While most global strategies focus on improving soil fertility, Rockström and Falkenmark (2015) urge an international high-level consideration of integrated crop water management. In fact, such water productivity improvements

(i.e. increasing the yield output per unit of water consumed) in both rainfed and irrigated systems paired with an increase in consumptive water use are a *sine qua non* for raising food production to the tremendous amount required (Molden 2007, IAASTD 2009).

However, the attainable extent and potential of integrated crop water management at the global level under both current and future climates remains insufficiently quantified (e.g. Pretty *et al* 2011, Rost *et al* 2009, IAASTD 2009, Brauman *et al* 2013). In this global modeling study we investigate the potential to increase yields through large-scale implementations of integrated crop water management (defined here as a mix of various farm water management interventions).

Particularly in semi-arid rainfed agriculture, subject to the largest water constraints to low yields, rainfall variability (dry spells, periodic water scarcity) often poses a much greater problem than the total amount of precipitation. In addition, in semiarid tropical systems root zone drought and low yields ($1\text{--}2\text{ t ha}^{-1}$) are often caused by poor farm water management with excessive on-farm water losses (Oweis and Hachum 2006, Rockström *et al* 2007, Wani *et al* 2009). Accordingly, the transpiration coefficient (TC, crop transpiration per unit rain and withdrawn irrigation water, figure 1) is often $<30\%$, as non-productive soil evaporation can consume up to 50% on low-yielding fields (Daamen *et al* 1995, Rockström 2003, Wani *et al* 2009), and 10%–30% can be lost to surface runoff (Welderufael *et al* 2008, Araya and Stroosnijder 2010).

These factors indicate key hydroclimatic opportunities. In fact, there is a portfolio of measures available to increase plant water availability through e.g. maximizing soil infiltration, minimizing soil evaporation, collecting surface runoff for supplemental irrigation, and improving irrigation systems (to expand irrigated areas using saved water). Supplemental irrigation during dry spells can trigger important positive production shifts (Fox and Rockström 2003, Biazin *et al* 2012, Burney *et al* 2013), and water harvesting (WH) and soil moisture conservation (SMC) techniques can double smallholder yields in drought-prone regions while at the same time improving resilience to climate risks (Rockström *et al* 2003, Oweis and Hachum 2006, Dile *et al* 2013). These long-known practices are being implemented sporadically around the world, leaving open vast potential to scale up (Barron *et al* 2015, Searchinger *et al* 2013, Mati *et al* 2007). Irrigated farming systems on the other hand, are the single largest global user of water abstractions (80%–90% of consumption), but they use water often inefficiently (Gleick *et al* 2009, Molden 2007). Irrigation improvements have the potential to save and redistribute water to underperforming systems (Rockström *et al* 2007, Kijne *et al* 2009, Brauman *et al* 2013, Jägermeyr *et al* 2015, Fishman *et al* 2015). In particular the combination of such measures, i.e. integrated farm

water management proved successful to boost yields across various farming systems (Oweis and Hachum 2003, Molden 2007, Mazvimavi *et al* 2008).

However, the potential significance of integrated crop water management at the global level remains unclear, because upscaling is a challenge given the heterogeneity of farming systems and downstream water trade-offs (e.g. Falkenmark *et al* 2001, Ngigi 2003, Pretty *et al* 2011, Dile *et al* 2013). Only few studies have used the capacity of modeling approaches in evaluating complex interactions of up-scaling water management interventions (e.g. Tsubo and Walker 2007, Kahinda *et al* 2007, Wissner *et al* 2010, Barron *et al* 2015). Lebel *et al* (2015) quantify WH potential for maize in the whole of Africa using an empirical approach. Rost *et al* (2009) simulate effects of WH and SMC on global crop NPP with the dynamic agro-hydrological model used herein. A knowledge gap remains, to provide a global assessment of integrated water management in rainfed and irrigated agriculture and using a large ensemble of climate change scenarios.

This study investigates systematically the global potential of integrated crop water management through implementing the most approved interventions into the dynamic global bio-agrosphere model, LPJmL. We present a process-based simulation of crop yields with high spatial, temporal and agronomic detail, explicitly accounting for downstream effects and catchment hydrology. The study shows by how much (i) global crop production could be intensified sustainably (in terms of not using additional water or land inputs), (ii) the water gap (see figure 2) could be closed, and (iii) these opportunities might buffer potential climate change impacts, assuming various ambition levels for large-scale adoption of integrated crop water management.

2. Methods

The representation of water harvesting, soil moisture conservation and irrigation transitions in LPJmL is outlined first (summarized in table 1), followed by basic characteristics of the model and the simulation setup.

2.1. Simulation of water management interventions

2.1.1. *Ex situ* water harvesting (WH_{ex})

This measure describes the concentration, collection, and storage of surface runoff in ponds or cisterns for supplementary irrigation (SI) during dry spells. Reservoirs are often sized to provide about 100–200 mm SI (Biazin *et al* 2012, Barron and Okwach 2005, Oweis and Hachum 2006). Its implementation is site-specific, depending on various biophysical, economic and social factors (Barron *et al* 2015, Studer and Linger 2013). We therefore simulate in LPJmL four

ambition levels for harvesting runoff during the growing season: on 10, 25, 50, and 85% of rainfed cropland in each grid cell with a maximum storage capacity of 200 mm, respectively. Case studies support similar up-scaling potentials across watersheds using gravity-fed and pump-based SI (Kahinda *et al* 2008, Barron *et al* 2015). We define a rather high storage capacity to allow evaluating SI potentials, despite challenges to its large-scale implementation (in section 3.6. we show that 100 mm suffice in 95% of all cases). Water is assumed to be reapplied on the same land where it was collected, if (i) root available relative soil moisture <40% of field capacity, (ii) daily precipitation is below 5 mm, and (iii) soil water supply falls short of soil water demand. Sensitivity analyses for the cistern size and irrigation threshold are displayed in figure S2.

2.1.2. *In situ* water harvesting (WH_{in})

Micro-catchment systems, e.g. pitting, terracing, micro-basins, but also conservation tillage, and mulching can hinder water from running off the field and thus help increasing infiltration capacity. Particularly the combination of micro-catchments and mulching is observed to reduce runoff and soil evaporation considerably (Botha *et al* 2007, Biazin *et al* 2012). In LPJmL, infiltration rate In depends on soil properties, current soil moisture and the infiltration parameter p . By default, without management interventions, $p = 2$, but here we also simulate increased infiltration rates assuming four different intensity levels ($p = 3, 4, 5, 6$).

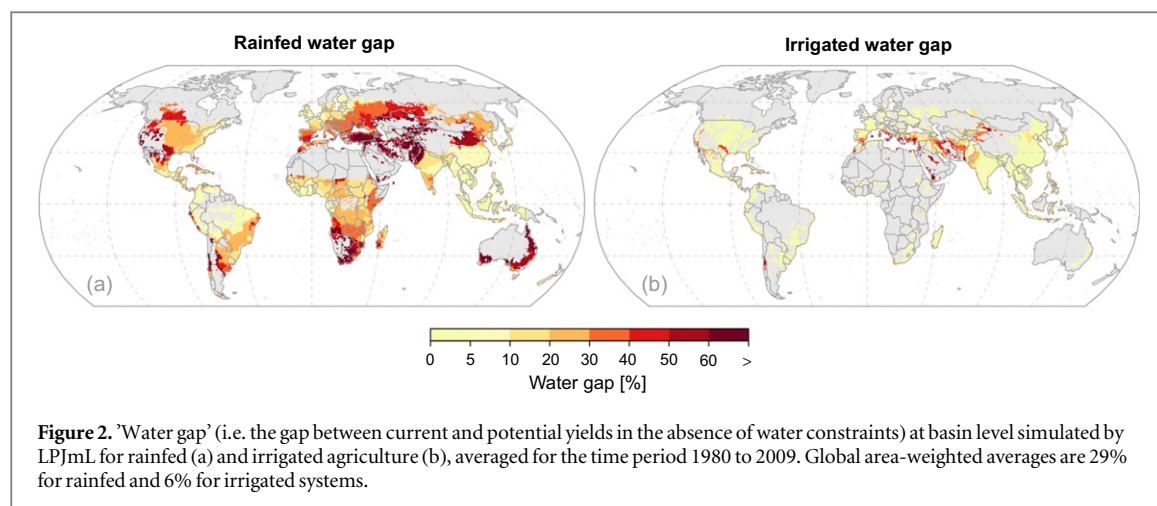
In is calculated for the upper soil layer as:

$$In = \text{prior} \times \sqrt[p]{1 - \frac{w_a}{W_{\text{sat}} - W_{\text{pwp}}}}, \quad (1)$$

where prior is daily rain and applied irrigation water, w_a is the available soil water content, and W_{sat} and W_{pwp} are soil water content at saturation and wilting point, respectively (all in mm). A sensitivity analysis for p is displayed in figure S2. Hereinafter, WH refers to the combination of WH_{in} and WH_{ex} measures at the four respective ambition levels.

2.1.3. Soil moisture conservation (SMC)

Non-productive soil moisture depletion can be alleviated through organic or plastic film mulching, and different conservation tillage systems. These techniques can improve grain yield remarkably through conserving soil moisture for additional plant transpiration, suppressing weeds, and improving cold tolerance (Liu *et al* 2014). Organic crop residues covering 50% of the soil surface can reduce soil evaporation by ~25%, plastic mulching can reduce soil evaporation by ~50%–90% (Bos *et al* 2007, Bu *et al* 2013). In our simulations, we reduce soil evaporation on rainfed and irrigated cropland during the growing season by 10, 25, 50, and 85%, respectively



(applied as a simple factor to the evaporation calculation). SMC is also applied on irrigated fields and therefore helps saving irrigation requirements. As it is not affecting downstream water availability, SMC can be considered a 'crop per drop' improvement also at basin scale.

2.1.4. Irrigation improvements and expansion with saved water (IRR_{exp})

Irrigation is represented through mechanistic simulation of surface, sprinkler and drip systems, depending on country and crop type. System efficiencies are directly linked to vegetation dynamics, weather and soil conditions, and water availability (Jägermeyr *et al* 2015). To simulate irrigation improvements, we define three theoretical transition scenarios:

- (1) **'50% surface'**, half of non-paddy surface irrigation is replaced by more efficient sprinkler systems.
- (2) **'Best practice'**, drip systems are established where applicable (based on crop suitability, (see Jägermeyr *et al* 2015)), the remainder is under sprinkler irrigation, but paddy rice remains with surface systems.
- (3) **'All drip'**, drip irrigation on all irrigated land.

Improving irrigation performances can release water which in turn can be exploited for expanding the target area. To calculate expansion potentials, we only consider saved water that otherwise would have been consumed non-beneficially, as irrigation return-flows are often crucial for downstream water availability. Expansion of irrigated land is assumed to be further constrained by current rainfed cropland within a river basin. Table 3 presents global numbers of expansion.

2.1.5. Integrated water management

In addition to individual simulations of water management interventions (sections 2.1.1–2.1.4), we run cross-combinations of WH, SMC, and IRR_{exp} (see table 2), from which we select three pointer scenarios

for further investigation and for climate change simulations:

- (1) **'Low'**: '50% surface' irrigation scenario + 25% SMC + 25% WH + irrigation expansion with saved water.
- (2) **'Ambitious'**: 'best practice' irrigation scenario + 50% SMC + 50% WH + irrigation expansion with saved water.
- (3) **'Max'**: 'all drip' irrigation scenario + 85% SMC + 85% WH + irrigation expansion with saved water.

It is worth to highlight that both the 'max', and 'all drip' scenarios are designed to evaluate planetary biophysical limits, not to represent feasible transition targets.

2.2. LPJmL model

The model LPJmL globally represents biogeochemical land surface processes of vegetation and soils (Bondeau *et al* 2007, Fader *et al* 2010, Jägermeyr *et al* 2015), simulating daily water and carbon fluxes in direct coupling with the establishment, growth, and productivity of major natural and agricultural plant types at 0.5° resolution.

Agricultural land is represented by 12 specified crop functional types (CFTs), a class 'others' that includes a suite of crops collectively parameterized as annual crops, and pastures (Bondeau *et al* 2007). All CFTs are either irrigated or rainfed and its spatial distribution and their irrigated fraction is prescribed as in Jägermeyr *et al* (2015).

Assimilated carbon (in the process of photosynthesis) is allocated to harvestable storage organs (e.g. cereal grain) and three other pools (roots, leaves, stems). Sowing dates are dynamically calculated based on climate and crop type (Waha *et al* 2012). Crops are harvested when they reach maturity, defined either through a CFT-specific maximum value of daily accumulated phenological heat units or expiration of the growing season. Storage organs are subsequently

Table 1. Selection of water (and soil) management interventions simulated in this study.

Name	Goal	Measure	LPJmL implementation	Rainfed / irrigated
Soil moisture conservation (SMC)	Alleviation of non-productive soil moisture depletion	Mulching (organic residues, plastic films), conservation tillage	Soil evaporation during growing season reduced by 10%–85%	Rainfed and irrigated cropland
ex situ water harvesting (WH_{ex})	Supplementary irrigation for dry spell mitigation	Collecting surface runoff in designated catchment area, storage in cisterns etc., supplementary irrigation	Surface runoff during growing season collected on 10%–85% of cropland (storage capacity 200 mm), suppl. irrigation if soil moisture <40% of field capacity	Rainfed cropland
in situ water harvesting (WH_{in})	Maximizing soil infiltration capacity and reducing non-productive surface runoff	Pitting, contouring, terracing, micro-basins, plowing, crop residues, conservation tillage	Increased infiltration rate (see equation (1))	Rainfed cropland
Irrigation improvement (IRR)	Reducing non-productive water consumption and using thus saved water for expansion	Improving performance of irrigation systems	Replacing surface irrigation with sprinkler or drip systems	Irrigated cropland, expanding into rainfed with saved water

removed from the field. Root growth and distribution within soil layers is CFT-specific, while the soil profile is discretized into 5 hydrologically active layers (Schaphoff *et al* 2013).

Plant growth is currently not directly nutrient-limited in LPJmL, yet constrained by temperature, radiation, water and atmospheric CO₂ concentration. We calibrate crop yields with national FAO statistics based on three model parameters (as in Fader *et al* 2010) to account for CFT-specific management intensities.

LPJmL partitions precipitation and applied irrigation water into interception, transpiration, soil evaporation, soil moisture, and runoff. Surplus water that cannot infiltrate generates surface runoff. Subsurface soil water above saturation runs off in lateral direction, while remaining soil water above field capacity percolates to the layer beneath, depending on its soil water content and hydraulic conductivity. Surface and subsurface runoff are accumulated along the river network and subsequently available for downstream reuse.

A recently implemented mechanistic irrigation module provides the framework for irrigation transitions (Jägermeyr *et al* 2015). In addition, we account for household, industry and livestock water use and include a representation of dams and reservoirs to improve the simulation of available surface water (Biemans *et al* 2011).

2.3. Simulation protocol

For the time period 1901–2009, we ran LPJmL forced with the Climate Research Units (CRU) TS 3.1

monthly climatology for temperature, cloudiness (Harris *et al* 2014) and with the Global Precipitation Climatology Centres (GPCC) precipitation data (Schneider *et al* 2014). The number of monthly rain days was derived from CRU and GPCC data as described in Heinke *et al* (2013). To cover uncertainties in climate change simulations (2009–2099), we considered four representative concentration pathways (RCPs: 2.6, 4.5, 6.0, 8.5), each being represented by 20 global climate models (GCMs) obtained from the CMIP5 multi-model ensemble dataset (table S2) (Taylor *et al* 2012). Monthly GCM output was bilinearly interpolated and bias-corrected to the reference period 1970–2000 using a method adapted from Watanabe *et al* (2012). To analyze the CO₂ effect on crop growth, each simulation was performed with constant (at year 2000) and transient CO₂ concentration. Model runs follow a 1000-year spinup (recycling the first 30 years of input climatology) and sowing dates are fixed during the simulation period after 1960 to allow the comparison of water management potentials between different runs and otherwise they would represent a form of adaptation not intended here.

Spatially explicit global information on cropland extent is obtained from the MIRCA2000 land-use dataset (Portmann *et al* 2010). The extent of areas equipped for irrigation from 1900–2005 is imported from Siebert *et al* (2015) and the distribution of irrigation systems from Jägermeyr *et al* (2015). Land use patterns are fixed after the year 2005. Irrigation withdrawal is constrained by local, renewable water storage, i.e. there is no implicit assumption about

Table 2. Overview of model simulations. RCP = representative concentration pathways, GCMs = global climate models.

Reanalysis climate 1901–2009		Simulations
ACT	Current management calibrated with FAO data, reference run for all other simulations.	1
POT	Potentially achievable yields under unconstrained water availability (nutrient deficiencies remain)	1
SMC	Soil evaporation reduced by 10, 25, 50, and 85%.	4
WH _{ex}	Surface runoff collected by 10, 25, 50, and 85%	4
WH _{in}	Infiltration rate increased in four sequential steps (equation 1)	4
WH	<i>ex situ</i> and <i>in situ</i> WH combined	4
IRR	Irrigation improvements: ‘50% surface’, ‘Best practice’, ‘All drip’	3
IRR _{exp}	Irrigation expansion using saved consumptive water from IRR	3
IRR _{exp} + SMC _{exp}	Irrigation expansion using saved consumptive water from IRR and SMC implementation	3
Combined	Cross-combinations of SMC, WH and IRR	12
Combined _{exp}	Cross-combinations of SMC, WH and IRR _{exp} + SMC _{exp} (include the ‘low’, ‘ambitious’, ‘max’ scenario)	12
Climate change 2009–2099: 4 RCP scenarios, 20 GCMs each, constant and transient CO₂ each		
CC	Climate change impact	160
CC + manage	Climate change plus water management scenarios: ‘low’, ‘ambitious’, ‘max’	480
	Σ	688

contributions from fossil groundwater or diverted rivers. Only potentially achievable yields (figures 2 and 4) are simulated under unrestricted water availability.

3. Results

3.1. Effects of integrated water management on crop production, transpiration coefficient, and the water gap

Simulated crop water management increases global kcal production by 41% under the ‘ambitious’ scenario (all measures combined, including irrigation expansion), while using existing agricultural land, yet cutting irrigation abstractions. Production increases by more than 55% in many river basins between the Middle East, central Asia, China, Australia, southern Africa and North and South America (figure 3(a)). Under the ‘low’ and ‘max’ scenario global kcal production increases by 18 and 60%, respectively (figure 3(b)). Individual effects of irrigation transitions (IRR), soil moisture conservation (SMC) and water harvesting (WH) are specified below (section 3.2. and the following).

On current farmland, we calculate the average transpiration coefficient (TC) at 46% for rainfed and 33% for irrigated systems (figure 1). Simulated water management significantly shifts water towards transpiration through alleviating soil evaporation, surface runoff and irrigation losses. Therefore, the TC (combined for rainfed and irrigated systems) increases from 42% to 49%, 54%, and 61%, respectively, in the ‘low’, ‘ambitious’, and ‘max’ scenario.

Production gains are particularly steep in regions currently experiencing large water gaps. Figure 2(a) highlights basins where the water gap exceeds 50%,

and include large parts of the Middle East, central Asia, North China plains, Australia, southern Africa, and the western United States. Based on LPJmL, current global rainfed farming operates with a water gap of 29% relative to its unconstrained water potential (yet neglecting nutrient deficiencies). In the ‘low’, ‘ambitious’ and ‘max’ scenario, this gap could be closed up to 17%, 11% and 5%, respectively (figure 4).

The irrigation water gap is necessarily smaller than the rainfed, as irrigation largely closes the gap. Under current conditions, global irrigated farming is simulated to be only 6% short of its unconstrained water potential (spatial patterns in figure 2(b)). While better water management can further narrow this gap (local significance), important benefits at the global level are associated with water savings (figure 4).

3.2. Water savings potentials of irrigation systems

Figure 5(a) confirms that improved irrigation and SMC implementations can only marginally increase irrigated production at the global level (by <2%). More importantly however, these measures (‘low’, ‘ambitious’, ‘max’ scenario without expansion) show the potential to cut consumptive losses (i.e. soil evaporation, interception, and evaporative conveyance losses) by respectively 24%, 48%, and 85% (figure 5(b)). This results in significant reductions of global irrigation withdrawal from currently 2507 km³ to 2071, 1248 and 808 km³ (figure 4), because alleviated soil evaporation and higher conveyance and application efficiencies strongly reduce irrigation requirements.

3.3. Irrigation expansion with saved irrigation losses

These water savings would theoretically allow for an additional 90, 345, and 597 Mha expansion into

rainfed cropland, respectively, for the ‘low’, ‘ambitious’, and ‘max’ scenario. These numbers are substantial in perspective of current irrigated land of about 300 Mha and the expected slow expansion pace. But future irrigation expectations are curbed due to land constraints under current system efficiencies (Alexandratos and Bruinsma 2012); farmers who pursue efforts to save water often use it to expand their irrigated share of cropland (Fishman *et al* 2015).

Global total kcal production (rainfed + irrigated) could thereby increase by 7%, 26%, and 43% with considerably higher numbers in specific basins particularly between the middle East, large parts of Asia, and Central to North America (figure 5(b); aggregated to the basin level, as upstream irrigation improvements can have water trade offs downstream). Note that irrigation expansion (with higher efficiencies), but also SMC and WH, lead to higher productive plant transpiration, which increases global irrigation water consumption from currently 1268 km³ to 1350, 1515, and 1607 km³, respectively (table 3, ‘low’, ‘ambitious’, ‘max’ scenario), while non-productive losses still decrease (not all saved water used up for expansion as some basins lack sufficient available rainfed cropland, figure 5(a)). Overall, the total global withdrawal amount is simulated to decrease by 128, 448, and 689 km³ for the three respective scenarios, despite the growth of irrigated areas (table 3).

3.4. Effects of soil moisture conservation and water harvesting on rainfed systems

SMC shows considerable potential to amplify rainfed kcal production (3%–14% globally, figure 6(a)). Regions with high sensitivity are concentrated in semi-arid to arid regions such as the Sahel, southern Africa, central Asia, and Australia, where production increases reach >20% (figure 6(b), no downstream effect and thus displayed at the grid cell level). As for water harvesting, WH_{ex} exhibits much higher production potentials compared to WH_{im}, but combining both measures appears especially beneficial at low intensity levels, and could increase global kcal production by 7%–24% (figure 6(c)). Figure 6(d) shows spatial patterns of WH (50% level) with high sensitivity also in semi-arid regions, but in addition in sub-humid regions with high rainfall variability and runoff excess, across tropical and temperate regions.

3.5. Climate change impact

Climate change is simulated to have adverse effects on global crop production, while high uncertainty is associated with the direct effect of carbon dioxide on plant growth. In simulations with constant CO₂ concentration (performed to isolate the climate change effect), global kcal production is projected to change by −3% (RCP 2.6) to −18.2% (RCP 8.5, table 4, median of 20 GCMs), mostly due to increased water deficiencies. With transient CO₂ concentration, a

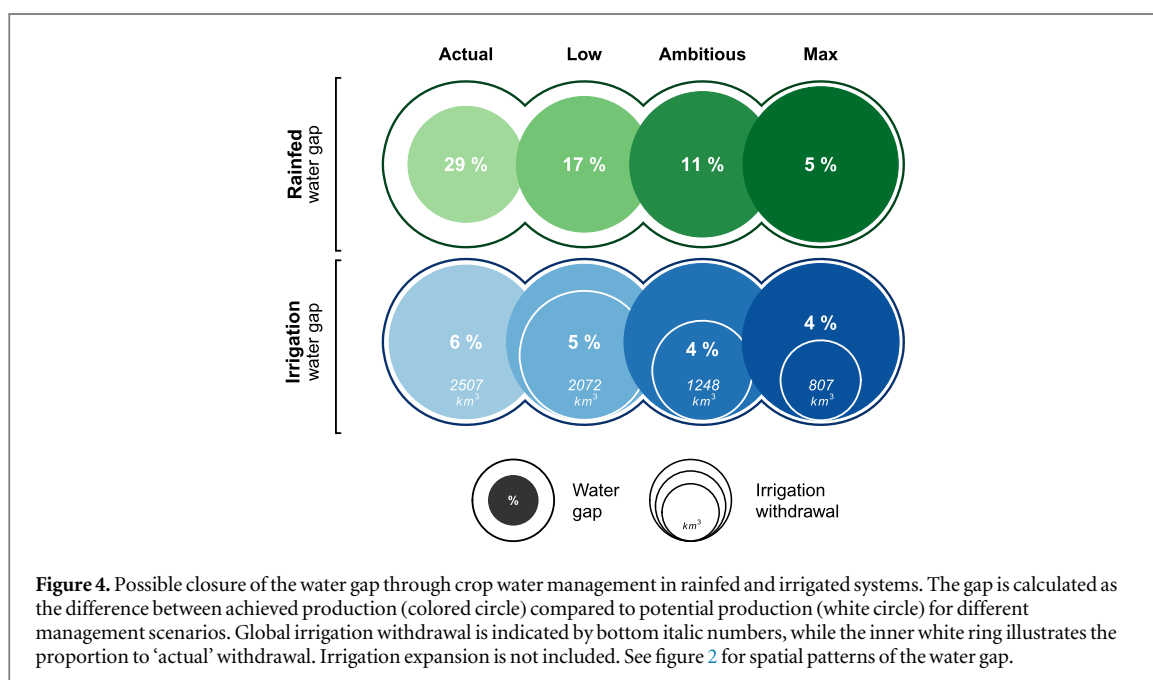
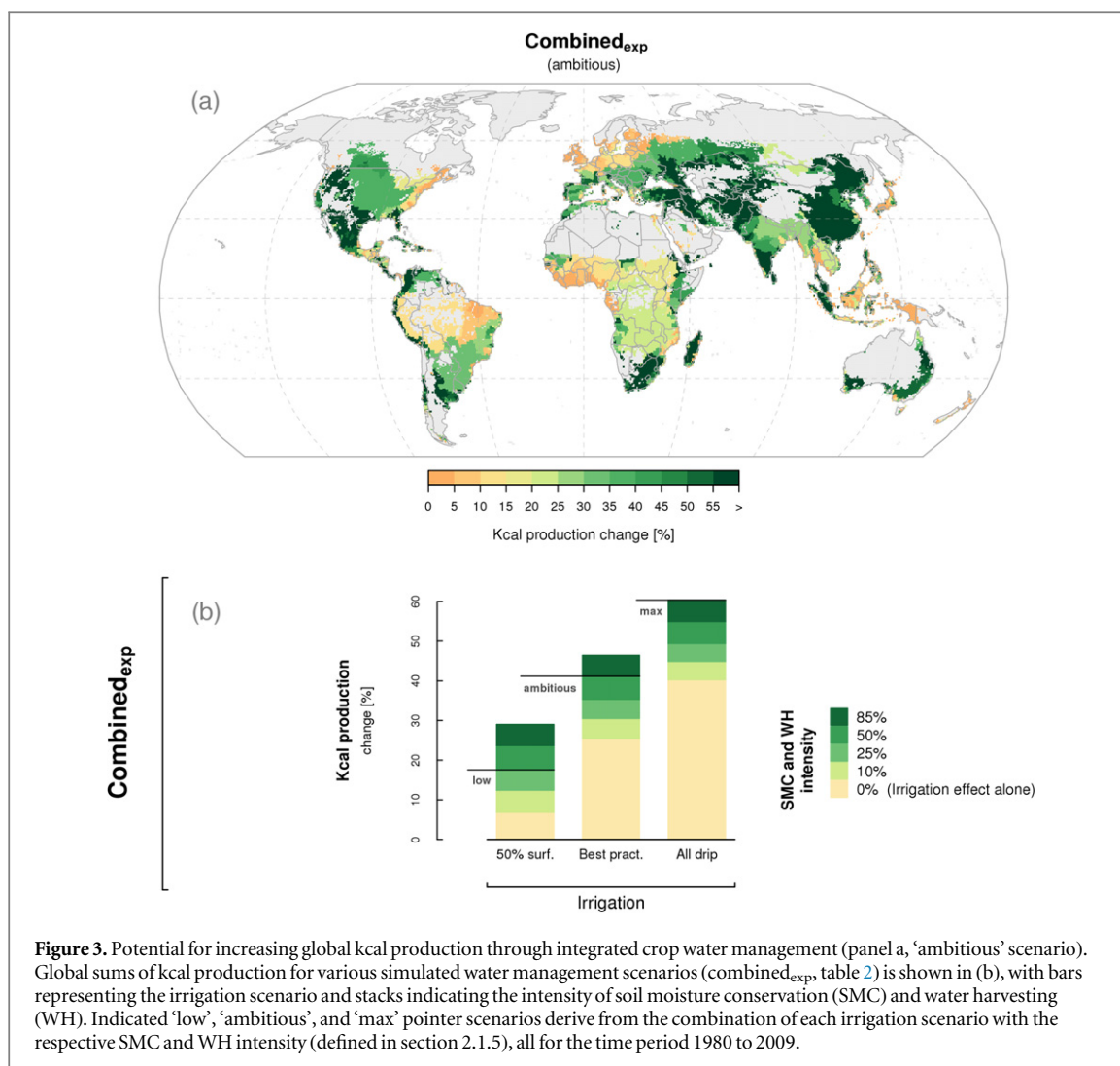
strong fertilization effect (in LPJmL not directly constrained by nutrient limitation) actually increases global production by 4.3% (RCP 2.6) to 13% (RCP 8.5) despite concurrent climate impacts. A ‘moderate’ CO₂ fertilization (mean of constant and transient CO₂ simulations) suggests marginal global production changes (−2.6% to 1.6%). Regionally however, India, Pakistan, west Australia, African Sahel, and east Brazil face negative changes from −5% to < −20% under RCP 2.6 (‘moderate’ CO₂), while strong increases occur in large parts of Russia, east and southern Africa, and parts of central and south America (5% to >20%). In an RCP 8.5 world (‘moderate’ CO₂) the Mediterranean region, major parts of the United States and Mexico, and southern Asia appear additionally on the map with distinct negative changes, and many basins show kcal declines from −10 to < −30% (figure 7(c)).

In the ‘low’ scenario, most adverse climate change impacts are simulated to be buffered in a RCP 2.6 world (figure 7, see figure S4 and S5 for constant and transient CO₂). The ‘ambitious’ scenario can ease negative impacts in an RCP 8.5 world in many basins, but some regions, notably east Brazil and west Africa, remain with negative impacts. Despite large uncertainties associated with the CO₂ effect, global crop production is simulated to increase by >40% under ‘ambitious’ water management for all but the most severe climate change scenario (35% with RCP8.5, table 4).

3.6. Evaluation of results and modeling issues

Supplemental irrigation, mulching, and conservation tillage demonstrably increased yields in case studies by 56%, 44%, and 30%, respectively (Araya and Stroosnijder 2010, Welderufael *et al* 2008, Fox and Rockström 2003). A major case study (286 projects in 57 countries) documents average yield increases by 79% through a number of conservation agriculture interventions, including water harvesting and conservation tillage (Pretty *et al* 2006). A wider collection of case studies shows similar ranges (table S1). Lebel *et al* (2015) simulate for maize in sub-Saharan Africa (SSA) an average yield increase with WH intervention of 9%–39%. We arrive at 0%–33% across SSA basins. In our simulation (50% level), on average 57 mm supplemental irrigation are applied during the growing season (in 95% of all cases less than 100 mm, figure S3), Fox and Rockström (2003) document 60–90 mm in a Burkina Faso case study. More generally we can reproduce the documented scale of observed yield gains using LPJmL, and our analysis extends case study insights to a broader set of climates, locations, and crops and thus refines management potentials at the global level (Rost *et al* 2009).

We point out that it is critical to evaluate the local feasibility of WH catchment and storage systems. This depends on different factors (e.g. terrain type, soil structure, hydroclimatic setting, social and financial



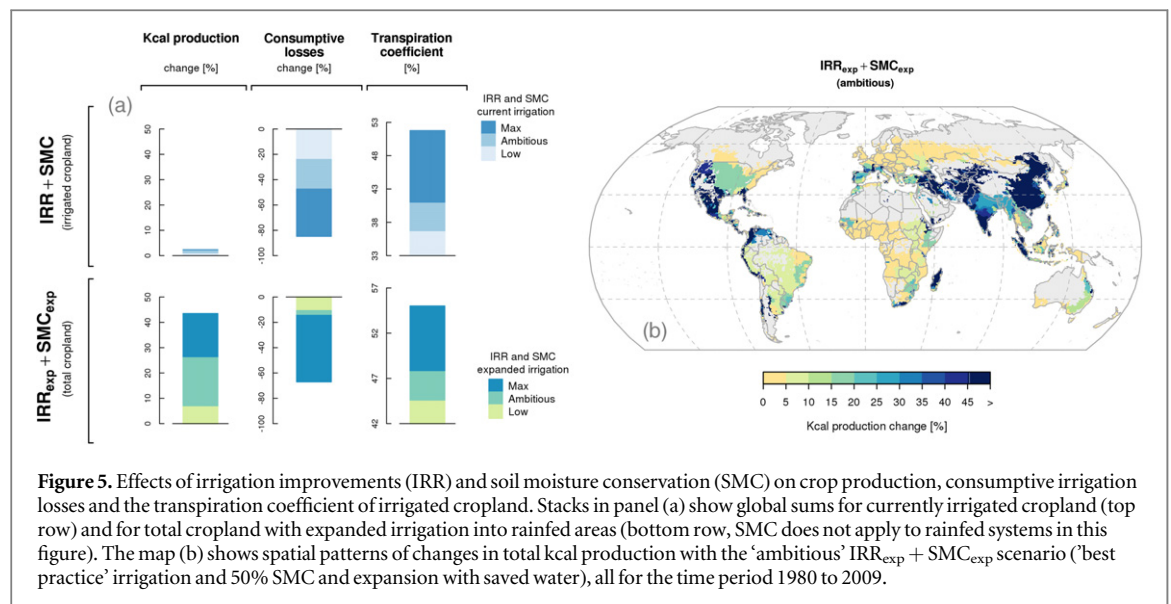


Table 3. Global area (*Mha*) of rainfed and irrigated agricultural land (including pastures) aligned with irrigation water consumption (IWC, km^3) and irrigation withdrawal (IWD), for current land use and the three scenarios of combined water management ‘low’, ‘ambitious’, ‘max’, including irrigation expansion (Combined_{exp} in table 2).

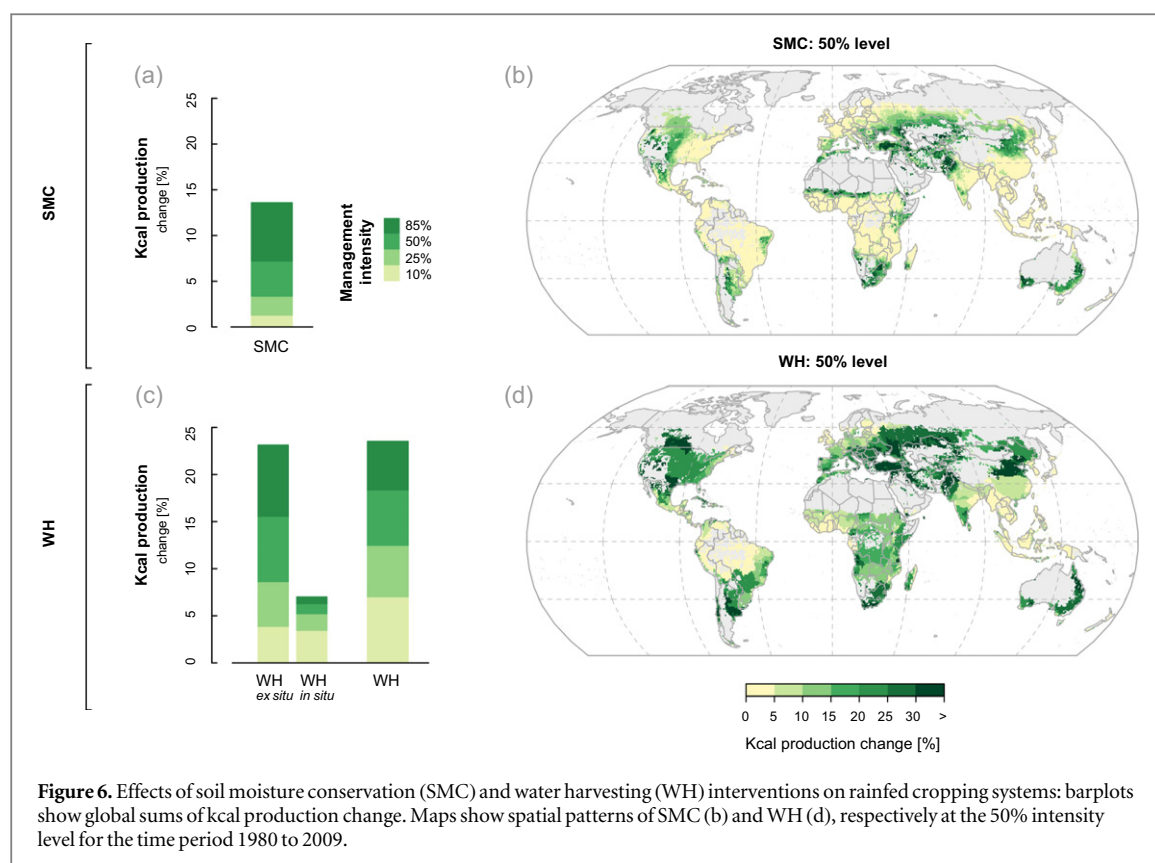
	Rainfed	Irrigated [Mha]	Total	IWC [km^3]	IWD [km^3]
Actual	3984	297	4282	1268	2507
Low					
‘50% surface’	3895	387	4282	1350	2379
irrigation					
+ 25% SMC					
+ 25% WH					
Ambitious					
‘Best practice’	3639	642	4282	1515	2059
irrigation					
+ 50% SMC					
+ 50% WH					
Max					
‘All drip’	3388	894	4282	1607	1818
irrigation					
+ 85% SMC					
+ 85% WH					

capital (Studer and Linger 2013, Falkenmark *et al* 2001, Mati *et al* 2007)), addressing those in detail is beyond the scope of this broad-scale study of biophysical potentials. Although case studies show that often only 10%-20% of the land is unsuitable for WH and SMC adoption (Barron *et al* 2015, Kahinda *et al* 2008, van Rensburg *et al* 2012), we might exaggerate WH suitability. However, this is faced by our very conservative assumption on the catchment area that is limited to existing cropland only, and which is often much larger in reality. But it appears infeasible to delineate additional suitable catchment areas with a sufficient degree of detail globally.

Therefore, we regard the ‘low’ and ‘ambitious’ scenario as potentially achievable, while the ‘max’ scenario, locally proven though, indeed appears unlikely to become implemented globally. Nevertheless, it provides important insights into planetary biophysical capacities. Furthermore, it is difficult to quantify the extent to which farmers already adopted WH and SMC measures. Although initial up-scaling projects prove successful regionally (e.g. Zhu and Yuanhong 2006), they still represent only marginal areas at the global level.

Our estimates of irrigation withdrawal and consumption agree well with previous estimates (FAO 2014, Döll *et al* 2014, Wada and Bierkens 2014), albeit featuring much more process detail. Irrigation expansion adds a noticeable share to production increases simulated in this study (figures 3(b) and 5(a)). The expansion of irrigated crops replaces rainfed crops, which results in a propagation of irrigated cropland into pastures in some cells, as the share of irrigated pastures is generally low. However, in SSA only 5% of the cropland is under irrigation today, which first explains our flat irrigation improvement potentials in SSA (figure 5 (b)), and second outlines scope for irrigation expansion using currently untapped water resources (FAO 2005, Burney *et al* 2013, Xie *et al* 2014).

Finally, it is important to note that upstream IRR and WH interventions can lead to reduced return-flows and runoff, which can negatively affect water availability downstream. Despite noticeable impacts locally, gains at the basin level over-compensate losses in all basins (figure S4). This appears beneficial from a food production perspective, but there is a clear need for policies and institutional orders to regulate water reallocations. In this context it is crucial to quantify contributions from groundwater and water diversions, given the complex recharge and transboundary issues involved.



4. Discussion

This study is the first to systematically quantify potential contributions of different strategies of farm water management to increase global crop production without increasing pressure on land and water boundaries. Based on spatially and temporally detailed process-based modeling, we advance the quantification of the global achievable scope of water management in rainfed and irrigated agriculture. Simulated yield potentials are well in line with farm-level experiences, but we exploit the dynamic modeling capacity of LPJmL for complex up-scaling of water interactions to arrive at robust global estimates. 41% production growth, at global scale, released through ‘ambitious’ water management outlines tremendous opportunities. While grand challenges lie ahead to its large-scale implementation, the ‘ambitious’ potentials simulated here appear feasible from a biophysical and also an agronomic perspective. More than 800 million people today remain chronically undernourished (United Nations 2015)—a kcal production gain of 40% realized by 2050 might be sufficient to halve the widening global food gap, assuming that we need 60%-100% additional crop calories to eradicate hunger (a gap of 80% roughly relates to 7.6×10^{15} kcal per year, compared to the production of 9.5×10^{15} kcal in 2006 (Alexandratos and Bruinsma 2012, Searchinger *et al* 2013)).

Although sustainable intensification appears high on the policy agenda, there is a lack of institutionalized

crop water management targets. In fact, such targets are outright missing from the recently passed sustainable development goals and from the supporting literature (United Nations 2015, United Nations 2016). Our study adds confidence that not targeting dedicated water goals means we are set to miss substantial opportunities to advance a sustainable food system and its climate resilience.

On the way towards a sustainable food future, water management is accompanied with essential co-benefits (that are not modeled here). Among the most important are reducing soil erosion through water harvesting and mulching, currently affecting ~67% of SSA cropland (Liniger *et al* 2011). But large-scale implementations of plastic mulching can also lead to environmental pollution (Liu *et al* 2014). Better irrigation technology helps reducing nutrients and pesticides application (better location and timing) (Christian-Smith *et al* 2012, Calderón *et al* 2014), while conservation agriculture in general will help mitigate greenhouse gas emissions (e.g. Mahdi *et al* 2015, Karimi *et al* 2012, Liniger *et al* 2011). Water management that leads to stabilized water supply throughout the growing season is prerequisite for smallholders to invest in higher inputs (fertilizer, breeds) (Biazin *et al* 2012, Burney *et al* 2013). Low-cost interventions (organic mulching, conservation tillage, simple drip kits) can directly translate in synergies in livelihoods; as most poor live in water-constrained agriculture, the associated scope for poverty alleviation and improved local food security is tremendous

Table 4. Potential climate change impact (CC) on global crop production as against three scenarios of water management under four RCP scenarios and different levels of CO₂ fertilization; for the time period 2070–2099 versus 1980–2009, as averages across 20 GCMs.

	RCP 2.6			RCP 4.5			RCP 6			RCP 8.5		
	const. ¹	moderate	trans.	const.	moderate	trans.	const.	moderate	trans.	const.	moderate	trans.
CC	−3.0	0.7	4.3	−7.6	0.9	9.3	−9.4	1.6	12.7	−18.2	−2.6	13.0
CC + manage												
‘Low’	12.6	16.2	19.8	8.1	16.4	24.6	5.8	16.7	27.5	−3.8	11.3	26.4
‘Ambitious’	38.4	42.2	46.1	33.1	41.8	50.5	30.8	42.2	53.7	18.9	34.9	50.9
‘Max’	53.1	57.3	61.5	47.1	56.7	66.2	44.6	57.1	69.7	31.4	49.1	66.8

¹ **Note.** const.: CO₂ concentration fixed at year 2000, trans.: transient CO₂ concentration, **moderate**: moderate CO₂ effect, mean yields of constant and transient CO₂.

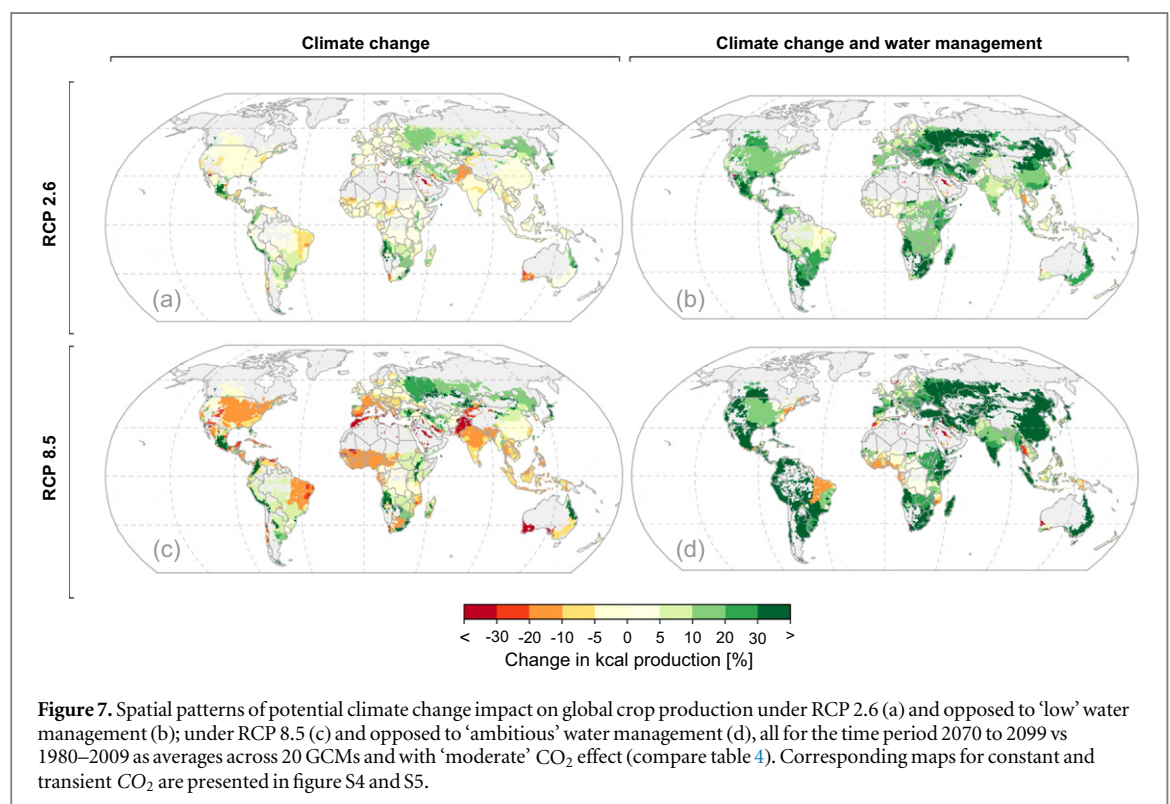


Figure 7. Spatial patterns of potential climate change impact on global crop production under RCP 2.6 (a) and opposed to ‘low’ water management (b); under RCP 8.5 (c) and opposed to ‘ambitious’ water management (d), all for the time period 2070 to 2099 vs 1980–2009 as averages across 20 GCMs and with ‘moderate’ CO₂ effect (compare table 4). Corresponding maps for constant and transient CO₂ are presented in figure S4 and S5.

(Postel *et al* 2001, Dillon 2011, Pretty *et al* 2011, Kahinda and Taigbenu 2011, Burney and Naylor 2012).

At the global scale, this study suggest that both smallholder on-farm techniques and large-scale improvements of irrigation systems and WH implementation are needed, while respecting environmental flow requirements of riverine ecosystems and other environmental boundaries. Our results show that large-scale adoptions of these measures lead into water reallocations that would benefit from institutional support and water legislations as mentioned above (Molden 2007). Future investments must focus on enhancing system productivity on current arable land, integrating management in rainfed and irrigated agriculture in an integrated landscape approach (Faurès *et al* 2007, Rockström *et al* 2007). Jägermeyr *et al* (2015) show that technical irrigation saving potentials are substantial at the global level, while in

this study we show that such savings could be redirected to support vast currently rainfed farms with additional irrigation water. Although initial investment needs are steep, long-term economic analyses confirmed the substantial net profits achievable (Biazin *et al* 2012, Fox *et al* 2005).

However, water management is not a panacea and needs to be combined with other components to sustainable farm management to exploit the strong synergy between water, soil and nutrient management (Oweis and Hachum 2006). Especially in SSA, many cropping systems are highly nutrient-deficient and water management cannot fully take off, unless depleted soils become replenished (Sánchez 2010, Fox and Rockström 2003). But it is clear that the challenge of achieving sustainable food security is not only a supply-side problem. Urgent action is also needed on holding down the growth in food consumption, reducing waste, and achieve replacement level fertility

(Garnett *et al* 2013, Searchinger *et al* 2013, DeFries *et al* 2015).

5. Conclusion

This study quantifies the significance of integrated crop water management at the global scale to intensify rainfed and irrigated farming. Simulated measures are constrained by the assumption that pressure on water resources and land does not increase, which delineates an effective strategy to minimize agricultural impacts on the biosphere. Based on detailed, process-based simulation of underlying local biophysical conditions and with high spatio-temporal resolution, we systematically investigate scenarios of irrigation improvements and expansion, water harvesting, and soil moisture conservation. Under a 'low' intensity scenario we arrive at a global kcal gain of 18%. With an 'ambitious', yet achievable scenario we reveal global production potentials of 41%. Such water management interventions would also about halve the current global water gap in agriculture. Moreover, thus improved water management offers the opportunity to buffer potential negative climate change impacts in many world regions. The 'low' intensity scenario might over-compensate climate change impacts under relatively low RCP 2.6 emissions (globally + 40% kcal production), while the 'ambitious' scenario could ease most negative impacts in a RCP 8.5 world (globally + 33% kcal production). Such kcal gain might be sufficient to halve the global food gap by 2050. In conclusion, this study highlights that not focussing on systematic implementation of integrated crop water management means to miss substantial opportunities in intensifying global farming systems within planetary boundaries and to negotiate climate-associated risks in smallholder agriculture.

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