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Projected water consumption in future global agriculture: Scenarios and related impacts

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ABSTRACT

Global stress on water and land resources is increasing as a consequence of population growth and higher caloric food demand. Many terrestrial ecosystems have already massively been degraded for providing agricultural land, and water scarcity related to irrigation has damaged water dependent ecosystems. Coping with the food and biomass demand of an increased population, while minimizing the impacts of crop production, is therefore a massive upcoming challenge. In this context, we developed four strategies to deliver the biotic output for feeding mankind in 2050. Expansion on suitable and intensification of existing areas are compared to assess associated environmental impacts, including irrigation demand, water stress under climate change, and the productivity of the occupied land. Based on the agricultural production pattern and impacts of the strategies we identified the trade-offs between land and water use. Intensification in regions currently under deficit irrigation can increase agricultural output by up to 30%. However, intensified crop production causes enormous water stress in many locations and might not be a viable solution. Furthermore, intensification alone will not be able to meet future food demand: additionally, a reduction of waste by 50% along the food supply chain or expansion of agricultural land is required for satisfying current per-capita meat and bioenergy consumption. Suitable areas for such expansion are mainly located in Africa, followed by South America. The increased land stress is of smaller concern than the water stress modeled for the intensification case. Therefore, a combination of waste reduction with expansion on suitable pastures generally results as the best option, along with some intensification on selected areas. Our results suggested that minimizing environmental impacts requires fundamental changes in agricultural systems and international cooperation, by producing crops where it is most environmentally efficient and not where it is closest to demand or cheapest.

1. Introduction

Agricultural production is currently accountable for 85% of global water consumption (Shiklomanov and Rodda, 2003) and projected to double by 2050 (Tilman et al., 2002). Irrigated area is expected to rise by a factor of 1.9 by 2050, while climate change is amplifying water stress by changing patterns of water availability in many parts of the world (Lobell et al., 2008). Finally, global production of biological energy resources is expanding and accelerates growth of agricultural production (Melillo et al., 2009). As a consequence of these pressures, water scarcity and land clearing represent major environmental concerns worldwide.

The environmental impacts of water consumption and water stress are manifold. While aquatic and water dependent organisms are directly affected by water abstraction, there are also significant indirect effects. For instance, terrestrial ecosystems downstream of the location of water use may suffer from water stress through reduced natural water availability and groundwater drop (Maxwell and Kollet, 2008; Costanza et al., 2007). Agricultural land transformation and occupation have direct ecological impacts on sites as well as on the surrounding landscape (Köllner, 2000). Generally, crop production deprives the land of most of its ecological value, e.g. through biodiversity degradation and disturbance of ecosystem functions.

Coping with population growth as well as additional per-capita food demand represents a major challenge in feeding humanity in the future: The world average caloric intake of about 2800 kcal per person-day in the year 2000 is judged adequate for average activities (Lundqvist et al., 2008). However there are still about 570 million people living in countries with an average of less than 2200 kcal per person-day, which is considered the minimal amount to meet basic nutritional needs (Loftas and Ross, 1995). Clearly, this situation needs to be improved, while at the same time taking care that the impact on the environment remains limited.

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Table 1
Specification of the strategies for agriculture in 2050.

	Case 1	Case 2	Case 3	Case 4
Goal	Feed global population	Feed global population	Feed global population	Feed global population with increased meat/biofuel production
Description	Intensification on existing agricultural land (including waste reduction)	Expansion to pastures	Expansion to pastures and natural ecosystems (e.g. forests)	Intensification, waste reduction and expansion to pastures
Increase of production on current agricultural areas	+26% agricultural output (I.4 in the Appendix). Calculated based on difference between output of optimal and current irrigation	–	–	See Case 1
Reduced food losses	Food losses after harvest and waste at distribution and household level reduced by 50% (based on Lundqvist et al., 2008)	–	–	See Case 1
Agricultural expansion	–	100% expansion on pastures which are at least *moderately* suitable for rainfed cereals according to (Fischer et al., 2000)	62.5% expansion on pastures and 37.5% on natural ecosystems; which are *highly* suitable for rainfed cereals according to (Fischer et al., 2000)	See Case 2
Crops involved in analysis	All 160 crops	Expansion of maize and wheat only, distribution based on analysis of most suitable cereal in each region (Fischer et al., 2000)	Expansion of maize and wheat only, distribution based on analysis of most suitable cereal in each region (Fischer et al., 2000)	All 160 crops for intensification; maize and wheat for expansion

The objective of the current paper is the evaluation of the environmental impacts of water and land use related to the future demand of agricultural goods. For this purpose, four strategies to increase food supply were modeled for the year 2050. The resulting four cases facilitated the evaluation of potential impacts on land and water resources of each of these strategies. Furthermore, the spatial distribution of land and water use was characterized and compared, to illustrate the environmental consequences and regional "hot spots" resulting from different actions. The results are intended to provide a basis for policies supporting the reduction of environmental impacts, while enabling agricultural production to feed the global population. We do not present best-guess scenarios.

2. Methods

2.1. Strategies development

Four cases were developed which all describe strategies to provide enough food for sufficiently feeding the future global population. It was assumed that distributional concerns are taken care of and that basic sustainability criteria are met, e.g. that no further land expansion is performed on rainforest area. Therefore, the strategies do not include the full range of possible developments, as several optimistic, sustainable assumptions are made. Rather, they serve as vehicles to evaluate and identify reasonable strategies to reach a desirable state of the future, in terms of world food supply.

To meet the future world food demand, global food provision needs to increase with population growth. We used an average of UN (UN Population Division, 2009) and U.S. census (U.S. Census Bureau, 2009) figures to project population growth from 6.1 billion in 2000 to 9.2 billion in 2050, which represents an increase of 51%. A total increase in food provision by 60% was assumed to be necessary to combat malnutrition.

Additional demand for food can be met with different strategies such as agricultural expansion, intensification, and waste reduction. In reality, these strategies will not be taken in isolation but in combination. However, to illustrate the environmental effect of both strategies, we developed separate cases: In Case 1, intensification on current agricultural area by increasing irrigation and fertilization as well as reduction of food waste was assumed. By contrast, Case 2 entails expansion only on pastures and Case 3 expansion on both, pastures and natural ecosystems. Finally, a fourth strategy was added where a combination of intensification and expansion was assumed (Case 4) allowing for increased per-capita consumption or for feeding a larger population. An overview of the characteristics of all four strategies is presented in Table 1.

Meat and dairy consumption was supposed to remain at the current level (around 500 kcal per capita and day) in Cases 1–3, as forecasts of increased meat consumption per capita were considered unsustainable.

In addition to meat and dairy, also the cultivation shares of biofuels and other non-edible crops, such as cotton or tobacco, were assumed to remain at the level of the reference year (2000) in Cases 1–3. Further expansion was considered unrealistic due to recognized negative effects on the environment from such cultivation, including pressure from high irrigation water use (Dominguez-Faus et al., 2009). However, non-edible crops could be cultivated at the expense of meat production, or when combining intensification and expansion to provide additional agricultural output for increased meat, fiber or biofuel production. Case 4 represented such a situation with higher material welfare but additional environmental burdens.

All strategies took the impact of climate change on precipitation into account. As there were many climate models available, we used the "multi-model average" predictions of precipitation change of the IPCC A1B scenario (IPCC, 2007a) for the 2050s (21 models, IPCC, 2007b). This approach best matched our assessments of population growth and socio-economic developments. In addition to the four cases with distinct strategies, a base case with constant food production (year 2000 level) was defined. The purpose of this case was to separately analyze the effects on water scarcity caused by changed crop water consumption due to climate change and due to projected increased domestic and industrial water use.

2.1.1. Case 1: Agricultural intensification and reduction of food waste

With this strategy, productivity on existing agricultural areas would improve by (i) meeting optimal irrigation water demand (assuming adequate fertilization where required) and (ii) reduction of food losses in the supply chain and at home by 50%, based on (Lundqvist et al., 2008). No agricultural land expansion was assumed.

2.1.2. Case 2: Pasture expansion

The expansion strategies presumed that increased food production would be supplied by doubling the current grain production from maize, rice, and wheat ($1.75 \cdot 10^9$ t of grain), as these crops provided about 60% of food calories (Loftas and Ross, 1995). However, in the analysis, expansion of rice cultivation was excluded. This choice was made, as rice production was mainly favorable over maize and wheat in areas with rainforests (Fischer et al., 2000) and our study rejected expansion to such sensitive ecosystems. In Case 2, agricultural expansion was assumed to occur on pastures which were reported to be at least moderately suitable for rainfed cereals production regarding climate and soil conditions (Fischer et al., 2000). This strategy assumed optimal irrigation that completely met crop water requirements (CWR) and proper fertilization on the expansion areas. No intensification of current agricultural area or enhanced production-chain efficiency was considered.

2.1.3. Case 3: Extensive expansion

Expansion was assumed to occur on pastures and natural ecosystems which were reported to be highly suitable for rainfed cereals production (Fischer et al., 2000), as opposed to Case 2 in which also moderately suitable areas were used. Further assumptions were equivalent to Case 2. Due to limited availability of pastures on highly suitable areas, 37.5% of expansion occurred on natural areas such as forests.

2.1.4. Case 4: Intensification and expansion (combination of Cases 1 and 2)

Increased productivity on existing agricultural areas by universally meeting irrigation water demands coupled with enhanced food supply and consumption efficiency (as in Case 1) were resulting an additional 60% of current food energy uptake. Agricultural output from expansion (as in Case 2) could provide another additional $1.75 \cdot 10^9$ t of grains available for increased biofuel or meat production. For maize processed as first-generation biofuel, this amount could replace about 7.2 billion GJ ($7.2 \cdot 10^{18}$ J) of fossil energy, assuming 4.1 GJ net fossil energy saving per tonne of maize (Pfister et al., 2011). This additional bioenergy corresponded to 1.4% of the world's current energy demand as reported by the Energy Information Administration (2009a) or 7.8% of liquid fuel consumption in global transportation in 2006 (Energy Information Administration, 2009b). Alternatively, this additional food energy could more than triple current meat and dairy production, and offer a doubled meat and dairy supply per capita in 2050 or feed a population of 12 billion people.

2.2. Model description

To model land and water use in the four cases a geographic information system (GIS) with a cell size of 5 arc minutes (less than 10 km, depending on the latitude) was used. Total water consumption (TW) and irrigation water consumption meeting the irrigation water requirements (also called blue water, BW) was calculated based on evapotranspiration, precipitation and plant-growth seasons, according to the CROPWAT model (FAO, 1999) (see I.1 and I.2 in the Appendix). Land use was calculated based on the yield and growth periods of the different crops according to Pfister et al. (2011) taking into account the length of actual growth period of the specific crops compared to length of natural growth period at the respective location. Corresponding land stress was derived applying a weighting based on potential net primary productivity of natural vegetation (NPP_0) to the calculated land use (see I.3 in the Appendix). Multiple crop rotations were only considered where already practiced in the year 2000 and intensification by expanding greenhouse agriculture was neglected.

2.3. Quantification and location of agricultural output in each case

2.3.1. Production increases through intensification (Cases 1 and 4)

The potential for increased production for each crop i ($\text{Prod}_{\text{increase},i}$ (%)) was estimated by the ratio of crop water requirements (TW_{max}) and the actual crop water consumption in the year 2000 ($TW_{expected}$), both modeled in Pfister et al. (2011) based on climate data of the "climate normal period" (1961–1990). We employed the equation and the crop-specific yield correction factors (k_y, Table S1 in the Appendix) from FAO (Doorenbos et al., 1986) to calculate changes in production amounts per crop i arising from increased irrigation:

$$\text{Prod}_{\text{increase},i} = \left(\frac{1}{1-\left(k_y \cdot \left(1-TW_{\text{expected},i} / TW_{\text{max},i}\right)\right)} - 1 \right) \cdot 100\% \quad (1)$$

The resulting overall relative increase in food energy production ($\text{Energy}_{\text{increase}}$) was calculated based on the average $\text{Prod}_{\text{increase},i}$, weighted by the absolute current production amount Prod_i of every crop i (Eq. (2)). As mass–energy ratio of different crops varies (e.g. significantly between tomatoes and wheat) we separately analyzed the $\text{Prod}_{\text{increase}}$ of the main cereals rice, wheat and maize (providing ~60% of all food energy, $i = 1$–3). $\text{Energy}_{\text{increase}}$ due to $\text{Prod}_{\text{increase},i}$ of the remaining 157 crops (providing ~40% of all food energy, $i = 4$–160) was assumed to be proportional to the annual production tonnage (Prod):

$$\text{Energy}_{\text{increase}} = \frac{\sum_{i=1-3} \left(\text{Prod}_{\text{increase},i} * \text{Prod}_i\right)}{\sum_{i=1-3} \left(\text{Prod}_i\right)} \cdot 60\% + \frac{\sum_{i=4-160} \left(Prod_{\text{increase},i} * Prod_i\right)}{\sum_{i=4-160} \left(Prod_i\right)} \cdot 40\% \quad (2)$$

According to our calculations, optimal irrigation on current crop patterns could raise agricultural edible energy production by 26%. In order to meet the goal of 60% additional edible energy demand without expansion, overall energy losses from field to fork needed to be reduced by a factor of 1.27: from currently 56% (Lundqvist et al., 2008) to 44%. Such increased food energy efficiency could be achieved by reducing harvesting losses and waste in distribution and households by 50%.

2.3.2. Production increases through expansion (Cases 2, 3 and 4)

The impacts of expansion were calculated based on projected yields for intensive maize and wheat cultivation based on (Fischer et al., 2000) (see section 2.1.2). The location of expansion was optimized based on best suitability for rainfed production and with priority on pastures.

As a side-effect, expansion on pastures led to decreased meat and dairy production. Therefore, we analyzed reductions in pasture production for Cases 2, 3 and 4 (I.5 in the Appendix) and estimated the resulting energy loss in animal food products as well as for the overall human diet (Table 2). The calculated loss in meat energy

Table 2
Loss of food from pastures due to transformation into cropland.

	Productivity loss of global pastures	Consequent meat and dairy output change[a]	Resulting change in total food energy due to changed meat and dairy output[b]
Case 2/4	−6.1%	−2.7%	−0.4%
Case 3	−3.7%	−1.6%	−0.2%

[a] 44% of fodder energy comes from pastures, based on (Wirsenius, 2003).
[b] Meat and dairy provide 15% of total food energy (Lundqvist et al., 2008).

revealed to be less than 3%, and corresponded to less than 0.5% of total food energy. These values indicated a minor relevance of this aspect and hence the potential decrease in meat and dairy production from transforming pastures into cropland is neglected.

2.4. Projected crop water consumption and related water stress

Changes in precipitation due to climate change and resulting changes in irrigation water demand were taken into account in all cases. For this purpose, we calculated the change in precipitation predicted by the IPCC "multi-model average" calculations for 2050 for scenario A1B (IPCC, 2007b) compared to the corresponding values of the "climate normal period" (1961–1990). These predicted precipitation changes are modeled on the "T42" resolution (ca. 2.8 arc-degree cell size) and subsequently interpolated to 5 arc-minute resolution for each month (see I.6 in the Appendix). Plant adaptation to changed temperatures, changed reference evapotranspiration, climate zone shifts and potentially increased plant-growth productivity due to increased CO_2-concentration in the atmosphere (Rost et al., 2009) were neglected in these calculations.

The concept of water stress index (WSI) as proposed by (Pfister et al., 2009) was used to assess the impact of water consumption on water scarcity in the watershed. WSI is a spatially resolved function of the withdrawal-to-availability ratio within each watershed, and was based on the WaterGAP 2 model (Alcamo et al., 2003). For the prospective WSI of the year 2050 (WSI_{2050}), two main factors needed to be considered: changed water availability through climate change and altered withdrawals due to changing human activities.

WaterGAP 2 results for the IPCC scenario A2 in the time span of 2041–2070 ("WaterGAP2050sA2") (Alcamo et al., 2007) were used for our calculations because the global precipitation change of the "ECHAM4-OPYC" model for scenario A2 applied in WaterGAP 2 in this period corresponded to the IPCC "multi-model average" calculations for 2050 in scenario A1B (IPCC, 2007b). However, it should be noted that regional differences among different models were large (IPCC, 2007b).

As the predicted population growth in the "WaterGAP2050sA2" was 25% higher than in the scenario A1B selected in this study, the change in withdrawals in each watershed was proportionally adjusted to the A1B population increase. In doing so, we assumed the total per-capita withdrawal in 2050 to be equal in the A1B and A2 scenario, according to the estimations of a previous study (Shen et al., 2008). However, this neglected that the two scenarios largely vary by assumptions on technological and socio-economic developments (IPCC, 2007a), leading to different regional patterns of water use. WaterGAP 2 projections did not cover expansion of irrigation while they assumed water efficiency improvements and included climate change (Alcamo et al., 2007). We therefore added the additional irrigation water use of our simulations for 2050 to the withdrawal calculations of "WaterGAP2050sA2". For this purpose, all additional irrigation water consumption required for the expansion and intensification in the different cases were converted to withdrawals, by globally assuming an optimistic irrigation efficiency of 70% (Hanasaki et al., 2008). Such efficiency could be achieved by using lined water distribution canals and sprinkler irrigation (Brouwer et al., 1989) or a mix of drip irrigation, sprinkler and flood irrigation systems. While our assumption reflected improved technological standards expected in the future, efficiencies of up to 95%, as achieved by drip irrigation (Postel et al., 2001), seemed not realistic on global average. Note that regional differences in irrigation water efficiency were not considered in the current paper.

2.5. Impact of increased land use

Land use was calculated based on the yield and growth periods of specific crops and the natural length of growth period (Pfister et al., 2011, described in I.3 in the Appendix). To assess the environmental impact of land use, we used an indicator based on the potential net primary productivity (NPP_0) of the used land, normalized by the global maximal NPP_0 value of 1.5 kg carbon/(m^{2*}year) (Haberl et al., 2007). Applied to land use, this indicator consequently presented the land use in equivalents of the most productive and hence absolutely scarce land areas of the world. It does not explicitly account for the ecological quality of land, such as biodiversity.

2.6. Comparing pressure from projected land and water use in agriculture

Environmental impacts from land and water use showed trade-offs. Yield maximization could result in irrigation with low water efficiency (Rockstrom et al., 2007; Doorenbos et al., 1986; Wisser et al., 2008) (Case 1). On the other hand, rainfed agriculture generally occupied more productive land than irrigated cultivation (Cases 2–3). Agricultural expansion could either be on productive ecosystems or marginal lands, with intensive and extensive production, respectively. For capturing these trade-offs and in order to quantitatively compare global agricultural production regarding use of land and water resources, a conversion factor was proposed that helped to express irrigation water consumption in terms of land-stress equivalents, i.e. equivalents of most productive land. Assuming that water availability contributed to the productivity of land as much as other parameters (e.g. temperature, soil properties and solar radiation), we derived the conversion based on the average precipitation of 2.50 m/year (Mitchell and Jones, 2005) on areas with maximal NPP_0 (>0.99), which are used as reference for land-stress calculations. The resulting conversion factor is hence 0.40 (m^{2*}year)/m^3, representing the time–area equivalent of most productive areas needed to replenish a certain amount of freshwater consumed. Analysis of average precipitation (1.05 m/year) and LSI (0.41) on agricultural land led to a conversion factor of 0.39 (m^{2*}year)/m^3, resulting in a good match with the conversion based on maximal values.

3. Results

3.1. Spatial distribution of production increase

3.1.1. Intensification strategy (Case 1)

The relative rise of crop water consumption for agricultural intensification as modeled in Cases 1 and 4 showed a distinct spatial distribution (Fig. 1): The highest potential for enhanced irrigation appeared in dry climates where deficit irrigation is currently prevalent. Accordingly, in such regions crop production could be raised the most. However, due to high water scarcity in these regions, the expected impacts from irrigation were most pronounced (section 3.3). Among the main hotspots of increased production were Western U.S., Australia, and Western China. Further details on crop-specific production increases are provided in Table S1 in the Appendix. Maize and wheat, which were often cropped in relatively dry climates, played the most important role, while rice production would only slightly increase.

3.1.2. Expansion strategies (Cases 2 and 3)

In both expansion cases production increased the most in Africa. Additional energy requirements in 2050 were covered by $1.43 \cdot 10^9$ t of maize and $3.2 \cdot 10^8$ t of wheat in Case 2, and by $1.46 \cdot 10^9$ t of maize and $2.9 \cdot 10^8$ t of wheat in Case 3. Wheat production expanded globally in Case 2 and mainly in Europe in Case 3 (Fig. 2, Figure S1 in the Appendix). For maize, however, production increases resulted mainly in expansion in Africa and partly in South America for both cases.

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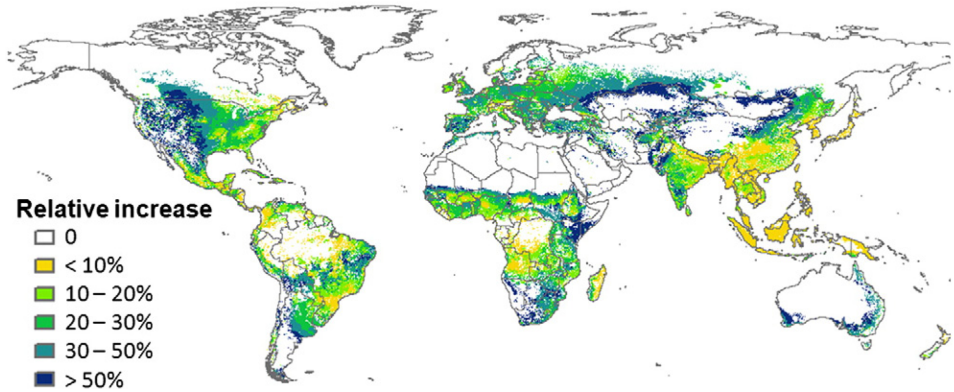

Fig. 1. Intensification: increase of crop water consumption of agricultural production in Case 1 compared to the year 2000.

3.2. Increased irrigation water consumption

Change in irrigation water consumption from 2000 till 2050 through climate change only (base case) is listed per continent in Table 3: Precipitation changes resulted in globally lower irrigation water consumption. However, there were regional differences. For instance, irrigation water consumption slightly increased in South America, Europe and Australia.

Still, combining climate change and additional crop production resulted a considerable global increase in annual irrigation water consumption of 1125, 169, 142 and 1294 billion m^3 in Cases 1, 2, 3 and 4, respectively as presented in Table 4: For Cases 1 (intensification) and 4 (intensification and expansion), the increase in crop cultivation tremendously expanded the current global irrigation water consumption of 1772 billion m^3/year (Pfister et al., 2011). Case 1 was thereby much more irrigation water-intensive than the current situation, in contrast to Cases 2 and 3 as expansion took place mainly on rainfed areas. In Case 4 (combining Cases 1 and 2) both agricultural outputs as well as irrigation water consumption were almost doubled. Thus, irrigation water intensity remained roughly constant.

The four cases showed substantial variations in spatial distribution of additional irrigation water consumption (Fig. 3). The expansion Cases 2 and 3 indicated most increases occurring in Africa and South America, while Cases 1 and 4 showed a less pronounced spatial pattern.

3.3. Water stress index projections for 2050 (WSI_{2050})

The water stress index (WSI) was used to roughly indicate areas of no (<0.1), low (0.1–0.4), moderate (0.4–0.6), high (0.6–0.9) and extreme (>0.9) water scarcity. The prospective WSI_{2050} values and their distribution showed remarkable differences depending on the

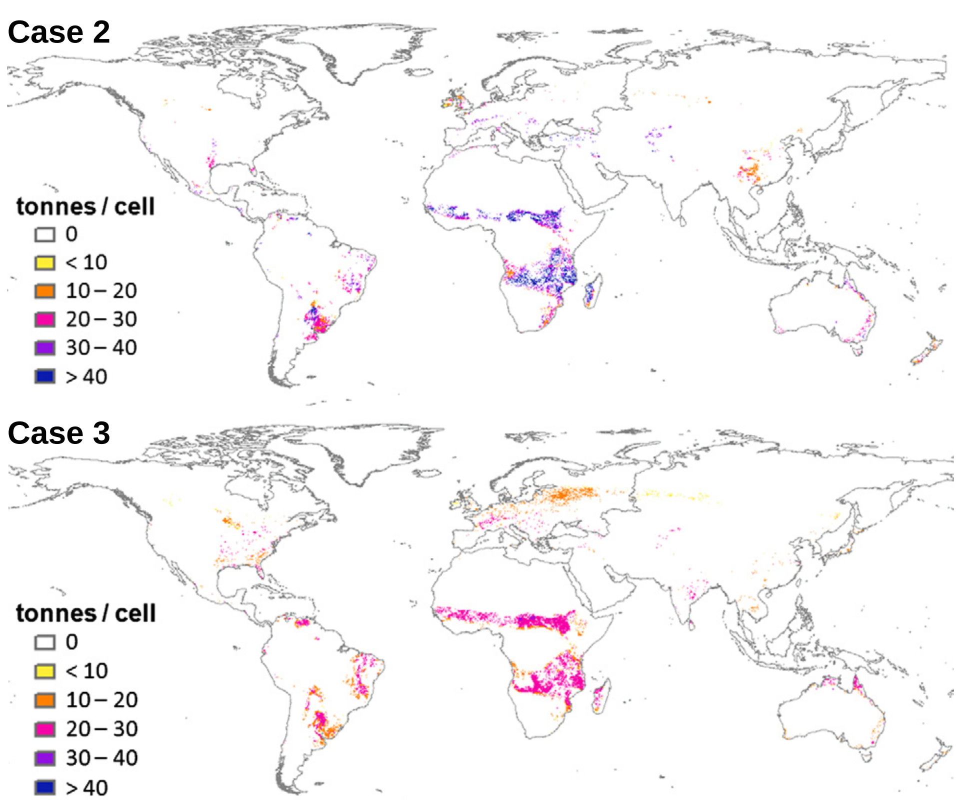

Fig. 2. Maps depict regions with increased grain production (sum of maize and wheat) reported as additional tonnes per grid cell (5 arc-minute grid): Case 2 (expansion on pastures which are at least moderately suitable for rainfed cereals) and Case 3 (expansion on pastures and other ecosystems on highly suitable areas for rainfed cereals).

Table 3
Continental sums of irrigation water consumption of the base case (only precipitation change, without change in crop production) for 2050 compared to the current situation in km^3.

Continent	Irrigation water consumption 2050	Irrigation water consumption 2000	Irrigation water consumption change of 2050 related the level of 2000
Asia	758	848	11% (−)
North America	293	300	2% (−)
Europe	227	216	5% (+)
Africa	207	243	15% (−)
South America	122	117	4% (+)
Oceania	0.193	0.269	28% (−)
Australia	49.3	47.9	3% (+)
World	*1656*	*1772*	*6% (−)*

strategies among each other and also compared to the base case of constant agricultural production (Fig. 4). The base case presented high WSI_{2050} values in arid or highly populated regions (e.g. Saudi Arabia and India). While increased irrigation intensity (Case 1) mainly added to water stress in the U.S., Europe, Eastern Australia and Western Africa, agricultural expansion (Case 2 and 3) raised water stress in Southern Africa and Eastern South America. The WSI_{2050} of combined intensification and irrigation (Case 4) was mainly driven by the intensification part except for Southern Africa.

3.4. Projected land stress

Fig. 5 shows the increase in annual land stress that occurred for Cases 2, 3 and 4. They featured a similar spatial pattern. However, exclusive expansion on pastures (Cases 2 and 4) was concentrated on fewer grid cells. Case 1 had no increased land stress, as no expansion occurred.

3.5. Combined impact on land and water resources

Combination of irrigation water consumption (expressed as land-stress equivalents) with land stress showed that water intensive production (Case 1) caused significantly higher environmental impacts per energy output, compared to expansion of agricultural lands on pastures and natural ecosystems (Cases 2 and 3, Table 4). However, analysis of the future land and water impacts caused by agriculture per unit of food energy supplied revealed that the specific combined land and water impacts were lower than in the situation of the year 2000, for each of the four cases (Table 4). Especially land impacts were significantly lower due to high-yield production and exclusion of expansion on the most productive natural areas.

4. Discussion

4.1. Methodological approach and uncertainties

In the present study, several cases were set up to meet future nutritional needs. These cases are not meant to be realistic predictions of the future, but rather they illustrate the environmental consequences of a range of strategic actions that may lead to a desirable state.

We evaluated these strategies focusing on two environmental impacts, namely land and water stress. Although we consider these two impacts to be crucial, agricultural activities have further environmental effects that are neglected in the present work, such as eutrophication, energy use and climate change or toxicity-related impacts through application of pesticides. These impacts have been shown to be relevant in previous studies (e.g. Melillo et al., 2009) and should therefore not be disregarded, but taken into consideration in combination with the results presented here. Additionally, all uncertainties related to the methods applied for the assessment of impacts from water and land use (Pfister et al., 2011) also apply to this study. For instance, while the indicators used reflect the impact on resource stress in terms of scarcity, impacts such as biodiversity loss are not explicitly addressed. Furthermore, land stress does not account for higher impact on environment of intensive agricultural production compared to extensive or organic practices, nor for irreversible or long-term impacts of land conversion from natural areas or pasture to cropland. However it provides a transparent quantification of land scarcity and impact related to occupation of productive land. This has been identified as one of the main environmental concerns in agriculture.

To resolve the trade-off between land and water consumption, a conversion factor was proposed. This conversion factor from water to land-stress equivalents needs to be interpreted with caution. While precipitation provides a transparent conversion based on natural water and land availability, it does not account for effective environmental impacts specific to terrestrial or aquatic ecosystems. Still, it allows comparing the trade-offs in a meaningful way.

Further uncertainties arise from the quantification of future water and land consumption, which depend on uncertain estimates of both, population growth and economic development. For example, population estimates for 2050 range from 8.7 to 11.2 in the different IPCC scenarios (IPCC, 2007a) and add substantial uncertainty on the demand side. These scenario uncertainties are considered to be crucial as they lead to a factor two between low and high estimates of increased global food demand.

The calculation of irrigation water consumption depends on climatic factors and is based on a straightforward calculation (FAO, 1999). The growth period parameters are adjusted to six major biomes which results in relatively low accuracy, especially along the borders of each zone. On the other hand, highly regionalized data on crop cultivation, precipitation and evapotranspiration are used to

Table 4
Global increase in annual total and irrigation water consumption and land stress (relative increase compared to the year 2000 is indicated in the brackets). In the year 2000, average WSI is 0.493 and total land-stress equivalent from land and water use is 4.49 million km^{2}*year.

	Case 1 (efficient intensification)	Case 2 (expansion on pastures)	Case 3 (rainfed expansion)	Case 4 (expansion and intensification)
Total water consumption (km^3)	1203 (+22%)	1088 (+20%)	1077 (+20%)	2291 (+42%)
Irrigation water consumption (km^3)	1125 (+64%)	169 (+10%)	142 (+8%)	1294 (+73%)
Average WSI	0.569	0.484	0.479	0.559
Land stress (1000 km^2*year)	None	552 (+14%)	534 (+14%)	552 (+14%)
Irrigation water land-stress equivalent (1000 km^2*year)	450 (+64%)	68 (+10%)	57 (+8%)	518 (+73%)
Total land-stress equivalent (land and water) (1000 km^2*year)	450 (+10%)	620 (+14%)	591 (+14%)	1070 (+24%)
Total land-stress equivalent/edible energy produced (m^2*year/1000 kcal)	0.28 (−13%)	0.23 (−29%)	0.23 (−29%)	0.21 (−33%)

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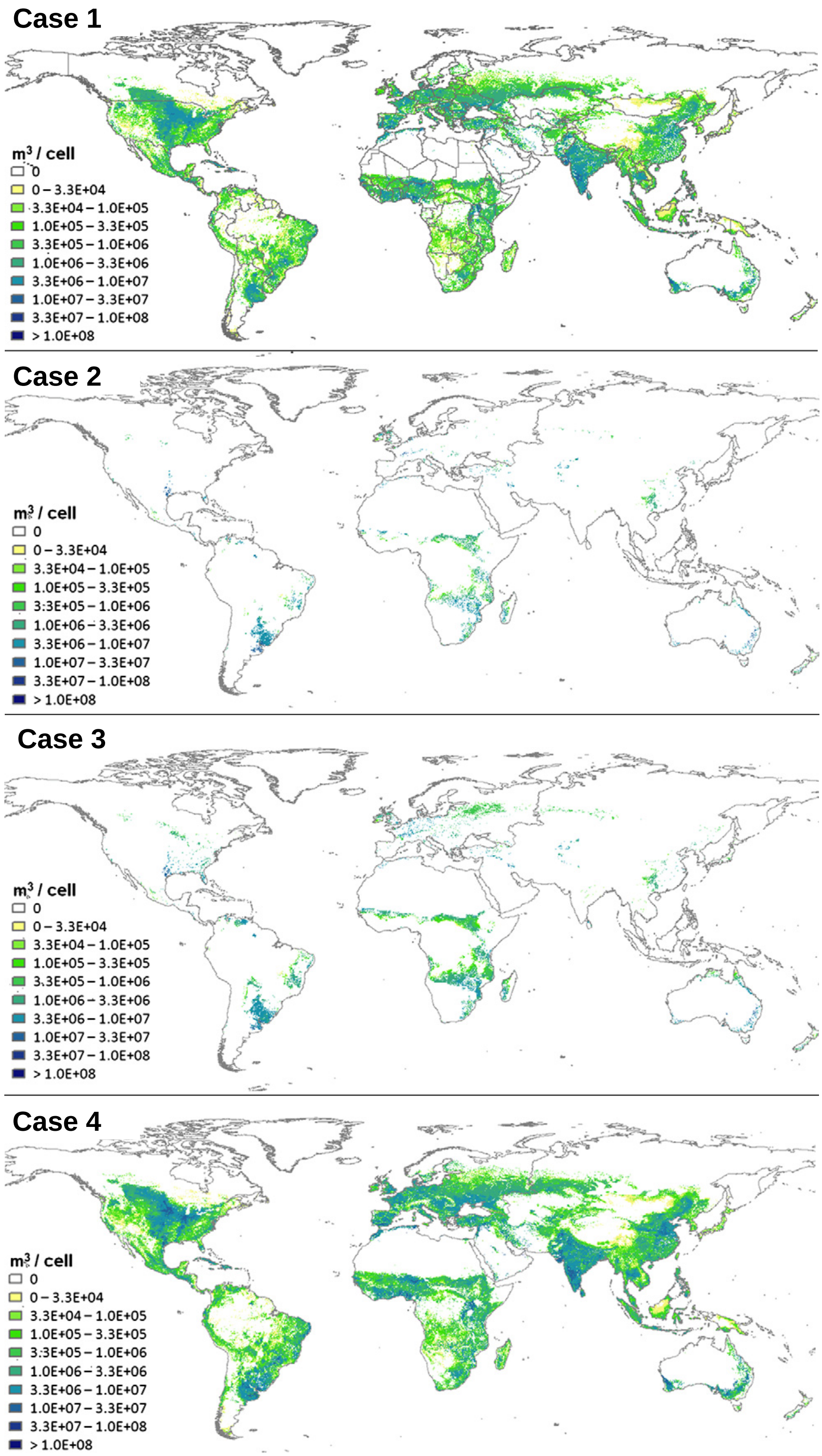

Fig. 3. Increased irrigation water consumption for each grid cell for the Cases 1, 2, 3 and 4 compared to the year 2000.

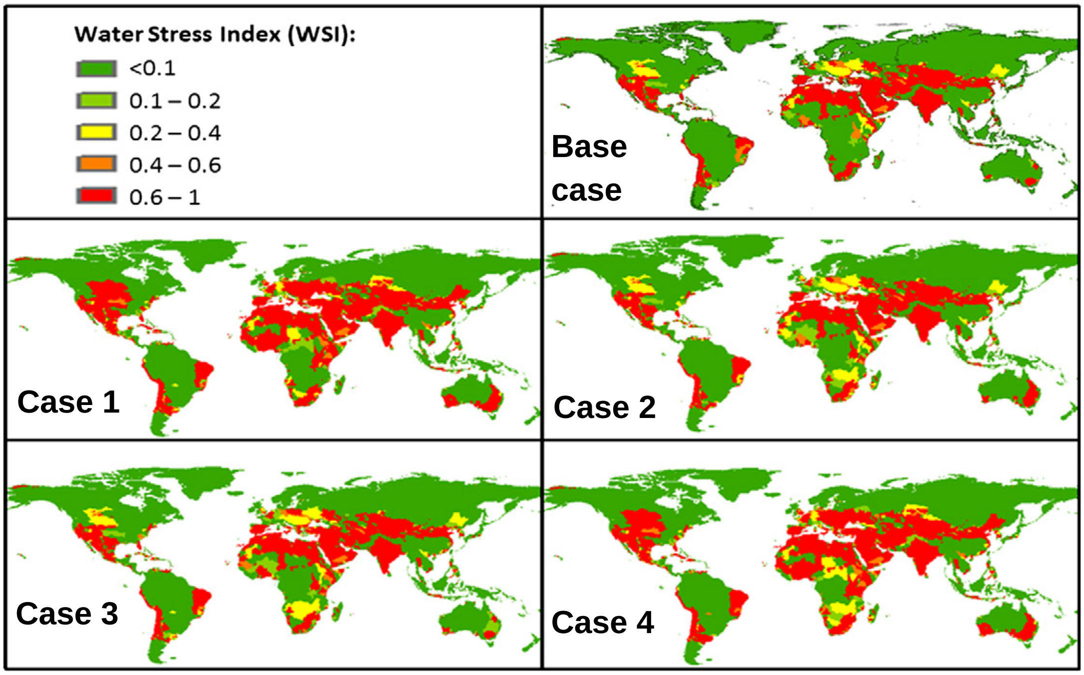

Fig. 4. Water stress index (WSI, dimensionless) of the projected cases for 2050, based on withdrawal and availability data from WaterGAP 2. The increased withdrawal due to expansion and/or intensification has been added based on the additional irrigation water calculation for each of the cases. The base case derived without increased production to reflect change of precipitation and industrial/domestic water use.

increase precision of the result. Thus, although simplifications are made, our estimations of water consumption are very advanced in terms of spatial resolution and number of crops considered. More uncertain seem predictions of water availability. The forecasts of 21 climate change models presented in the IPCC reports are diverse and often project different trends. Therefore, considerable uncertainties are attached to the adopted average monthly precipitation forecasts. Predictions of reference evapotranspiration are even less certain and

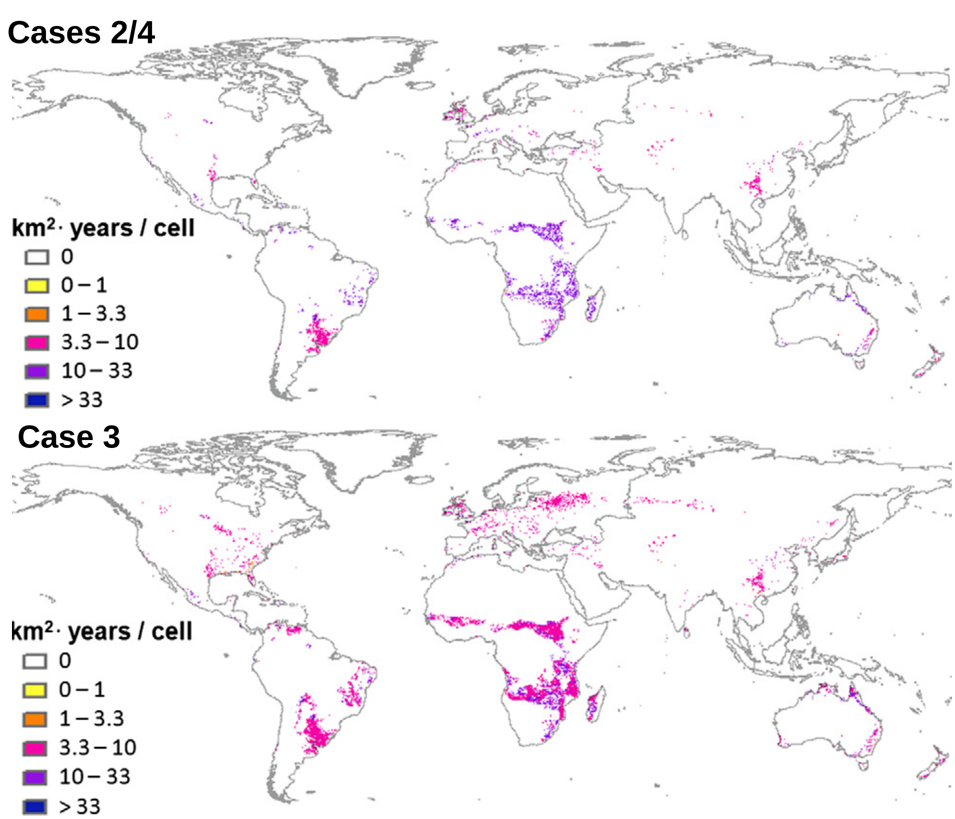

Fig. 5. Increased annual land stress due to expansion measured as km^2· year per grid cell (5 arc-minute grid): exclusive expansion on pastures in Cases 2 and 4 (top) and on pastures and natural ecosystems in Case 3 (bottom).

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therefore no change is included in the crop model. However, compared to the uncertainties related to the scenario selection and case development, these limitations are considered less relevant for the results of this study.

A critical parameter for land and water use modeling is the crop-specific yield. Good agricultural practice is assumed for both, the yield improvements for intensification based on the k_y factors as well as the modeled yields for expansion of maize and wheat production. Such positive development might not be achieved in practice everywhere, resulting in higher land and water use per food energy output. In this context, concerns about long-term soil fertility of areas transformed from pasture to agricultural land need also to be considered. This adds uncertainty to the selection of appropriate expansion areas, especially regarding soil organic carbon, erosion losses and sustainable fertilization. While transformation of pastures has been selected including constraints of soil features, such as textures and soil phases, the underlying soil maps are of limited quality (Fischer et al., 2000) and fertilizer provision might be problematic in many of the expansion regions. In addition to the eutrophying effects of fertilizer application, phosphorus (P) supply has often been characterized as a rapidly depleting resource (e.g. Cordell et al., 2009; Vaccari, 2009). However, recent estimates (U.S. Geological Survey, 2011) suggest no "peak phosphorus" problem in the 21st century, even with a large increase in fertilizer use. Furthermore, proper P recycling as e.g. from waste water treatment plants and food waste might considerably reduce the mineral fertilizer demand. There is also a large reduction potential on the application side, as the P input to global agriculture is higher than the output (MacDonald et al., 2011) and e.g. the phosphorus use efficiency in the U.S. food system is only 15% (Suh and Yee, 2011). Nevertheless, fertilization might become an economic issue due to potentially increased prices of P and potassium (K) from low-quality mining as well as high energy requirements for producing inorganic nitrogen (N) fertilizer. These issues should be addressed in future research.

An additional uncertainty source is induced by neglecting the climate-dependence of yield, as we neither account for increased yields due to CO_2-fertilization nor effects due to temperature increases. Negative temperature effects have been addressed by Lobell et al. (2008) mainly based on statistical analysis with high uncertainties due to data quality constraints. Schlenker and Lobell (2010) offer more detailed assessments for five staple crops in Sub-Saharan Africa and found temperature effects to be significant, except for cassava. Overall the expected yield losses were in the range of 10–20%. However, their analysis also showed that exchanging staple crops might help limiting such losses and new breeds might be able to perform better under climate change. In this paper, changed cropping patterns have not been analyzed and add uncertainty to the cases as does the simplification of limiting the expansion to wheat or maize cultivations in Cases 2–4.

For the assessment of future water stress index, water use efficiency of 70% was applied globally. This does not account for the regional differences of irrigation facilities and might overestimate water use in areas with highly efficient technology while under-estimating water use in regions with poorly developed irrigation schemes. Compared to the uncertainties discussed above, this source of uncertainty seems to be of lower concern.

Important to note is that cultivating crops where it is most suitable for environment rather than where it is closest to demand or cheapest, results in changed and potentially increased trade flows. Enhanced trade affects socio-economic conditions and might also lead to further food losses or increased energy use, which has not been considered in this study.

Finally, not all possible actions to increase agricultural production or lower food demand were considered by our four cases. For instance, changes in dietary demand (e.g. reduction of meat consumption) or optimization on crop choice and rotations on currently occupied land were not considered here.

4.2. Strategy comparison

Global irrigation water consumption needed to increase agricultural production was by a factor of 7–9 higher for intensification (Cases 1 and 4) than for expansion (Cases 2 and 3). These results reflect the benefit of rainwater use on expansion areas. By contrast, Case 1 had no additional impact from land use, while in Cases 2 and 3 land stress increased considerably. Thus, the trade-off between land- and water-related impacts of both strategies, expansion and intensification, is obvious. Case 3 (rainfed expansion) has comparable impacts on water and land use as Case 2 (expansion on pastures), although it included $2 \cdot 10^5$ km^{2}*year of land stress from currently natural areas. This expansion on natural ecosystem might be weighted higher regarding its environmental value and metrics for this should be explored in future.

Important to note is that Case 1 did not produce the same amount of food on the field but improves food supply chain by minimizing waste. Also the expansion cases could have been coupled with waste reductions, leading to less environmental impacts. A mix of expansion and intensification (such as Case 4) indicates that future relative increase in pressure is likely to be higher on water than on land resources, provided that — as assumed in all cases — rainforests and other unique ecosystems are protected. Water stress is driven mainly by increased water consumption, while precipitation changes due to climate change are of minor relevance. In absolute terms of land-stress equivalents per food energy produced, increased pressure by water consumption in the intensification case is higher than land stress from the expansion cases (Table 4).

In Case 1, irrigation water consumption increased mainly in Asia, followed by North America, Europe and Africa. By contrast, irrigation water consumption as well as land stress mainly increased in Africa and South America for Cases 2 and 3 (Figure S1 in the Appendix). These findings underline the need to advance agriculture of developing countries, in particular in Africa and partially also South America, to better distribute agricultural activities in favorable regions and alleviate future environmental problems of hotspots. While, from a nutritional point of view, the expansion on pastures currently used for meat and dairy production has only a minor impact on overall food energy provision (Table 2) it might cause severe social and cultural problems e.g. for nomadic cultures which are depending on pastures. Such problems are not considered in this study.

As the resource consumption per edible energy was considerably lower in all cases compared to current production (Table 4), cases without such improvements might feature 20–50% higher global impacts. Additionally, expansion on rainforest and other unique ecosystems or concentrated overuse of water resources might lead to a much worse picture, way beyond the level of Case 4.

In any case, the increased efficiency is overcompensated by the absolute increase in agricultural activities. For instance, compared to the current production volume (base case) the area of severely water-stressed regions will significantly increase, especially in the intensification Cases 1 and 4 (Fig. 4), and create a large challenge for water resource management in those areas.

4.3. Comparison with other studies

Our analysis represents cases of good practice with strict boundary conditions (e.g. fair global distribution of resources) and selected measures to increase agricultural production. A combination of these measures might be used to derive strategies for supply of agricultural goods in 2050. We compared the outcomes of our results to studies analyzing best-guess scenarios. Regarding water consumption there are large differences in the available studies: while e.g. Molden (2007) and Shen et al. (2008) predict a large increase in irrigation water consumption of 622 and 718 km^3/year, respectively, for 2050 (applying an irrigation efficiency of 70%), Sauer et al. (2010) modeled additional 181 km^3/year until 2030. Falkenmark et al. (2009) predict additional irrigation water consumption of 430 km^3/year by 2050, while accounting for land expansion of 281 Mha. Our results range from 142 km^3/year to 1293 km^3/year of additional irrigation water consumption, embracing these estimates. Regarding land use, the 281 Mha in Falkenmark et al. (2009) is low compared to 450 Mha predicted for 2050 by Rockstrom et al. (2007). A recent review of different model outputs for land use change by 2030 compared to the year 2000 reported additional crop production on 125–265 Mha in 2030 (Lambin et al., 2011). As we applied a land-stress index and modeled land occupation as "area * time" instead of calculating cropland increase, the results cannot directly be compared to other studies. Our expansion scenarios feature land stress of 53 and 55 Mha*year. Using the average LSI of current cropland (0.4) and a cultivation period of 0.75 years to convert land stress to land transformation results a cropland expansion of 177 and 183 Mha, respectively. For 2050, these values are on the lower end and reflect the high yields assumed for the high-input agriculture (fertilization and irrigation) in our expansion cases. From that perspective, the results are in good match with estimates in literature and also demonstrate the improvement potential achievable through best-practice agriculture.

5. Conclusions

Our cases illustrated potential consequences of increasing agricultural production on a detailed and highly spatially resolved level. Thereby, they provided a transparent evaluation of potential future agriculture for policy making. The study reveals possibilities to decrease the specific environmental impacts with good agricultural practice and well distributed expansion and/or intensification on existing cropland. Increased production potentials are mainly located in developing countries, in particular in Africa and parts of South America. In order to be able to feed the future generations, it seems therefore necessary to develop agriculture in these regions. Still, land or water resources (and most likely both) will become increasingly stressed and therefore natural resources need to be managed wisely.

Given the overall water and land-stress increase, drought resistant crop varieties, improved rainwater harvesting, and water conservation should be fostered, especially in semi-arid tropical regions (Rosegrant and Cline, 2003) which are suggested for the lion share of increased agricultural production through intensification. However, with technical improvements as required for intensification, there is a risk that increased production will be favored over concentration on a smaller area. In this context, the local and global perspectives need to be coupled: The presented results can assist comparative analyses of and decisions about intensification or expansion in agriculture. In combination with local natural resource management and socio-economic studies, our results can also support decision-making about where investment in agriculture works best in a global context.

Considering that our strategies are based on assumptions of good agricultural practice and positive socio-economic development (e.g. fair distribution of food resources), huge obstacles for implementation exist. However, our strategies illustrate that, provided these challenges can be overcome, it is principally possible to supply enough food for 50% more people on earth, without the need of rainforest cut-down. In particular, the reduction of the incredible share of food that is currently wasted (56% from field to fork) could bring enormous benefits. Also, agricultural expansion into suitable areas for rainfed cultivation has a high potential to save water and alleviate water stress (Table 2). This result provides hope but also shows that an immense amount of water and land is required and needs to be managed wisely for satisfying the additional food demand.

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Appendix A. Supplementary data

Additional methods and results are available in the supporting online material as indicated in the text. We also provide the raster data tables of the maps in Figs. 1–3 and Fig. 5 (see detailed description in I.7). Supplementary materials related to this article can be found online at doi:10.1016/j.scitotenv.2011.07.019.

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