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# Water, climate and food production

*Scientific justification of the information produced for the chapter 'Water and food production' of 'The Geography of Future Water Challenges' (2018), The Hague: PBL Netherlands Environmental Assessment Agency.*

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## **Main messages**

- Availability of water is a critical prerequisite for food production, both for the production of crops for direct human consumption and feed for livestock.
- Two thirds of the world's crop production come from rainfed areas, encompassing 80% of the arable land, and one third from irrigated areas, encompassing 20% of the arable land. The major part of the water used in agriculture comes from precipitation (*green water*).
- The water yield gap (i.e. the difference between actual yields and potential yields in the absence of water constraints) is much larger for rainfed agriculture than for irrigated agriculture. For irrigated agriculture, this gap is partly closed by adding *blue water* (surface water and groundwater).
- Globally, around 60% to 70% of the withdrawn fresh water (blue) is used for agriculture.
- Non-renewable withdrawals are largest in the Middle East and Northern Africa, with around 75% of total withdrawals in a few provinces, and the areas that depend on the available water sources are projected to expand in the future, due to climate change and an increasing demand for water.
- Future increases in global population (from 7 to 9 billion) and per-capita food consumption will require a strong increase in crop production, over the period up to 2050. At the same time, climate change will regionally change the conditions for food production through seasonal changes in temperature and water availability, generally resulting in i) improved conditions for food production in northern, moderate zones, and ii) reduced food production in tropical regions, especially those where water availability decreases (e.g. dryland regions).
- In areas where the growing demand for food cannot be met through improvements in land, crop and water management up to 2050, the area of cropland will increase at the expense of natural vegetation. This is the case in South and Southeast Asia, Central America, the eastern part of Brazil, and in sub-Saharan Africa, with arable land expansions of 20% to 50%.
- In some of those regions, such as in India, the south-eastern part of Brazil and Nigeria, a high percentage of land area is already in use as cropland (60%–80%). This percentage is expected to further increase, over the coming decades, which will increase the pressure on biodiversity and competition for land.

- Due to climate change in combination with population growth, the water-related yield gap (defined as the difference between actual crop yield and the potential crop yield in absence of any water constraints) is expected to increase predominantly in the dryland areas of Asia, Africa, the United States and South America, and in the densely populated non-dryland areas in East Asia and South Asia. Without any action being taken on this subject, water scarcity in the last regions may hamper economic development (OECD, 2017).
- Regions with very intensive agricultural systems, such as South Asia, are often also suffering large water-related yield gaps. Improved water management could be very beneficial, especially in these regions.
- There is a strong competition between the water that is needed for food production and that required to sustain aquatic ecosystems. Major water efficiency improvements in both rainfed and irrigated agriculture could compensate for the negative impact on crop production and eventually lead to a global net production gain of 10%. Nevertheless, Northern India and Central Asia, in particular, would experience a decrease in crop production of 20% to 30%—even after major improvements in rainfed and irrigation water management.

### 1.1.1 Introduction

#### **Feeding a growing global population – Importance of water and land**

Safeguarding the future production of food for a growing population under a changing climate poses a major challenge. The availability of fresh water is one of the most important conditions for agricultural production and, therefore, a prerequisite for ensuring a sufficiently high food production level. This water can either come from precipitation only (rainfed agriculture) or it can be supplemented with water from rivers, lakes, reservoirs or groundwater (irrigated agriculture). A shortage of water directly leads to a loss in crop production. To compensate for this loss, more arable land will be needed. Alternative means need to be found to either increase water availability or decrease water demand.

Whether regions are unable to ensure a sufficiently high production level to feed their population, now and/or in the future, depends on many factors, both biophysical and socio-economic. Climate change will affect potential crop productivity, due to seasonal changes in temperature and the amount of water available for this purpose. Population and GDP growth will lead to a higher demand for food, and will therefore impact the cropland extent and the total volume of water needed for agriculture, whereas technological changes might increase the potential productivity and water efficiency of crops. Regions where crop production is not very reliable due to a high variability in water availability are particularly vulnerable when they do not have sufficient water storage capacity or the means to import food. Regions that fully depend on rainfed agricultural production (mostly dryland areas), generally, are more sensitive to variability in water availability than those with irrigated croplands. What is more, a low level of self-sufficiency and a high dependence on imported food can make a region vulnerable to conflict and violence (see document on Water, climate and security).

The development of scenarios on future food production and the identification of vulnerable areas with respect to water availability, therefore, require an integrated assessment with explicit investigation of all relevant factors. At the same time, the identification of vulnerable areas is not straightforward, because of its multi-dimensional character. This background document discusses the various aspects and definitions of hotspots of vulnerable food production and identifies hotspot regions, globally, focusing on water availability only. A suite of indicators is presented under various climate and socio-economic scenarios.

### **Trends for wheat, maize, rice and soya bean**

According to the IPCC (2014), peer-reviewed literature studies show that there is a medium level of confidence about climate trends having negatively affected wheat and maize production in previous decades, in many regions. There is also a medium level of confidence about the negative impacts on global aggregate production of wheat and maize. Between 1980 and 2008, changes in temperature caused reductions in global yields of maize and wheat of 3.8% and 5.5%, respectively, relative to a counterfactual without climate change, which, in some countries, offset some of the gains from improved agricultural technology (Lobell et al., 2011, in: IPCC, 2014). Effects on rice and soya bean yields have been small, both in major production regions and around the global (IPCC, 2014). There is limited direct evidence unambiguously linking climate change to impacts on food security (IPCC, 2014).

### **Northward expansion crops**

Warming has already caused a northward expansion of crops in Europe. This was shown for silage maize and grain maize in southern parts of Scandinavia (Odgaard et al., 2011; Elsgaard et al., 2012; Eckersten et al., 2014; Nkurunziza et al., 2014, all in: (Olesen, 2016)). Analyses of the effects of observed climate change on yield potential in Europe have shown positive effects for maize and sugar beet, which have benefited from the longer growing season for these crops (Supit et al., 2010, in: (Olesen, 2016)). Yield benefits have been greatest in Northern Europe. The warming may also have contributed to higher potato yields in northern regions of Europe. In contrast, warmer and more variable climatic conditions with increased occurrence of drought have reduced crop yields in parts of Central Europe (Eitzinger et al., 2013, in: (Olesen, 2016)).

### **Pests and diseases**

Not only crops but also pests and pathogens move poleward. Between 10% and 16% of global crop production is lost to pests, with similar losses postharvest (Flood, 2010; Oerke, 2006; Chakraborty and Newton, 2011, all in: (Bebber et al., 2013)). From an analysis of published observations of 612 crop pests and pathogens, it was concluded that the average poleward shift in recorded incidences of these pests and pathogens since 1960 is  $2.2 \pm 0.8$  km/year for the northern hemisphere and  $1.7 \pm 1.7$  km/year for the southern hemisphere (Bebber et al., 2013). Overall, there has been a significant trend of increasing numbers of pest and pathogen observations at higher latitudes, globally and in both the northern and southern hemispheres. Although recent climate change is implicated as an important driver of these observations, other factors could bias the results. For instance, new crop varieties and agricultural technologies have extended the agricultural margin northward in the United States, and deforestation has increased production in the tropics, thus providing new opportunities for pest invasions at high and low latitudes (Bebber et al., 2013).

### **Food, water and the SDGs**

A shortage of global water and land resources for food production *directly* relates to a number of Sustainable Development Goals:

- SDG 1. No poverty: Water and land constraints on food production can lead to poverty when food production is insufficient to provide in people's livelihood and feed the local population. Reduced income due to reduced agricultural food production in combination with rising food prices, for instance, affect especially the poor. Also, the economy of nations largely depending on food exports may be negatively affected by decreased crop production.
- SDG 2. Zero hunger: Constraints to local food production may lead to hunger when self-sufficiency of food production cannot be realised, dependency of external food supply increases and requirements in import, transport and distribution are not met (cf SDG 1).
- SDG 3. Good health and well-being: An adequate availability and variety of food is an important factor for good health and well-being. When self-sufficiency of food production cannot be realised, and when countries cannot afford to import food on a large scale, the local population may turn to a one-sided diet and/or have too little food.
- SDG 6. Clean water and sanitation: Water related ecosystems and irrigation compete for water in regions where water is already scarce. Increasing water use efficiency is a prerequisite in water

scarce regions in order to increase food production without negative impacts on aquatic ecosystems.

- SDG 7. Affordable and clean energy and SDG 13. Climate action: Economic development, improving social conditions and combating climate change requires the intensification of renewable energy production. In the water and food domain, developing hydropower and expanding the production of energy crops may on the one hand contribute to providing clean energy, but may on the other hand compete with water and land for food production and nature (document on Water, climate and aquatic-biodiversity risks).
- SDG 11. Sustainable cities and communities: Sustainable production of sufficient (varied, good quality) food to feed the local and urban population is a prerequisite for a community to be sustainable.
- SDG 12. Responsible consumption and production: Sustainable intensification of food production is a prerequisite for i) providing enough good food; ii) reducing environmental impacts; and iii) protect and conserve natural terrestrial habitats (SDG 15) and aquatic habitats (SDG 14).
- SDG 14. Life below water: Efficient and sustainable use of both land and water (SDG 12) are a prerequisite for protecting and conserving aquatic habitats and biodiversity (document on Water, climate and aquatic-biodiversity risks).
- SDG 15. Life on land: Sustainable intensification of food production (SDG 12) is a prerequisite for i) providing enough good food; ii) reducing environmental impacts; and iii) protect and conserve natural terrestrial habitats. The world's most densely populated areas already have a high percentage of land in use as cropland. This percentage is projected to increase further, at the expense of nature areas (Figure 7).

Global water and land constraints on food production also relate to a number of Sustainable Development Goals in an *indirect* way:

- SDG 8. Decent work and economic growth: Poor countries where self-sufficiency of food production cannot be realised are caught in poverty. They have insufficient means to strengthen their economy, and are thus unable to create enough and good jobs for their population.
- SDG 9. Industry, innovation and infrastructure: This SDG is strongly related to SDG 8. Lack of enough (good quality) food is a constraint to economic growth, and hence to options to invest in industry, innovation and infrastructure.
- SDG 16. Peace, justice and strong institutions: When food production is not sufficient to feed the local population, reduced food availability, deteriorating livelihoods and rising food prices may contribute to social insecurity, changing migration patterns and possibly violent conflict (see document on Water, Migration and Conflict).

### 1.1.2 Objective

This study was conducted with the aim to identify current (2010) and future (2050) hotspots of vulnerabilities for food production related to water availability. The identification of these hotspots was based on the results of an integrated assessment of the effects of climate change, population growth, economic development and land-use change.

This report presents a set of selected indicators related to various aspects of land and water constraints on food production. It provides estimates of changes in the amount of water required for agriculture, and the fraction of this demand that cannot be met or is withdrawn from non-renewable resources. It subsequently presents an estimation of the impacts of water shortages (related to climate change) on food production. The report introduces the *water yield gap* to express the yield reduction or loss that results from this water shortage. It presents the major crop producing areas of the world, and regions where changes in agricultural areas are expected in order to meet future food demand. Finally, it shows the current and future food production per capita as a measure of the potential level of self-sufficiency of countries.

### 1.1.3 *Methods and analysis*

In this study, we use the IMAGE model, a model framework that simulates the environmental consequences of human activities worldwide (Stehfest et al., 2014). It estimates, amongst others, the future extent of rainfed and irrigated cropland, resulting from changes in climate and socio-economic factors, and leading to a change in food demand. IMAGE is fully coupled to LPJmL, a global hydrology and vegetation model (Bondeau et al., 2007; Gerten et al., 2004), which calculates global water availability (in rivers, lakes, reservoirs and renewable groundwater), water demand from various sectors, as well as the effect of water shortages on crop production, at a high spatial (0.5 degree) and temporal (daily) resolution. This makes the coupled IMAGE-LPJmL model a very suitable tool for studying the relationship between water availability, food production and land use, i.e. the land-water-food nexus.

We use IMAGE-LPJmL to estimate current and future food production and agricultural water use under different climate and socio-economic conditions. The spatial pattern of climate change is calculated in IMAGE internally, but is forced to follow the Representative Concentration Pathways (RCPs) 2.6, 6.0 and 8.5 (Van Vuuren et al., 2011). In addition, a set of storylines for the socio-economic developments, what are known as Shared Socio-Economic Pathways (SSPs) 1, 2 and 3 (Kriegler et al., 2012), are used to estimate future food demand, production and international trade. The RCPs and SSPs are presented in detail in a separate document. Time slices of the calculations are 2001–2010 (for the 2010 situation) and 2046–2055 (for the 2050 situation).

The allocation of future cropland depends on the growing demand for food, the projected change in import and export in a region, the expected increase in crop productivity due to improved management and the suitability for cropland expansion.

Because the original SSPs did not include estimates for the expansion of irrigated area, nor for the increase in irrigation efficiency, we estimated these developments in a consistent way, aligning them with the storylines of the SSPs and existing studies. The projected increase in irrigated cropland for SSP2 ('middle of the road') is derived from a recent FAO study that estimates irrigation development per country based on historical developments and expert judgements (Alexandratos and Bruinsma, 2012). For SSP1 and SSP3, we applied lower and higher increase rates for irrigated cropland area respectively (Doelman et al., 2018). The improvement in irrigation efficiency, i.e. the ratio between the water needed by the crop and the water actually withdrawn to irrigate the crop, depends on the rate of expansion of irrigated land and other SSP assumptions with respect to sustainability. We assume that new irrigated land will be equipped with more efficient irrigation systems than the old ones, and that the improvement goes faster in SSP1 as it describes a development towards a more sustainable world (Doelman et al., 2018).

In the first part of our assessment, we focus on changes in water supply and demand. In most areas of the world, the expansion of irrigated area will lead to an increase in irrigation water demand, despite an increase in irrigation efficiency. First, we compare the expected change in agricultural water demand with expected withdrawals for other sectors (Bijl et al., 2016). Second, we estimate the change in water availability due to climate change and upstream withdrawals. LPJmL explicitly distinguishes different sources for irrigation water withdrawal: water in rivers and natural lakes (Rost et al., 2008), artificial reservoirs (Biemans et al., 2011) and renewable groundwater. The third step shows the fraction of water for irrigation that should be withdrawn from non-renewable water sources if we assume that all of the irrigation demand will be met.

The second part of our assessment focused on the food production and related current and future water shortage to local reductions in food production. First, we show how climate change will impact crop yields on current agricultural land. Subsequently, we show how food production is distributed globally now (2010), and what we expect for the future (2050). We estimate the expected changes in terms of total cropped area and absolute crop production. In order to present a measure for a country's dependency on food import, we also show the per capita crop production.

### 1.1.4 Results

## WATER

### Current (2010) and future (2050) water demand

Figure 1 shows the expected global development in water demand for irrigated agriculture as well as the global total water demand, including from industry, electricity generation and households. The changes in irrigation water demand in all SSPs are the net effect of changes in climate, irrigated area extent and irrigation efficiency. The increases in the water demand from other sectors are especially high in SSP2 and 3, and decrease after 2050 in the projections for SSP1. Note that Figure 1 reflects water *demand*, which is not the same as water withdrawal. Withdrawals can be lower than the demand, because of the unavailability of water.

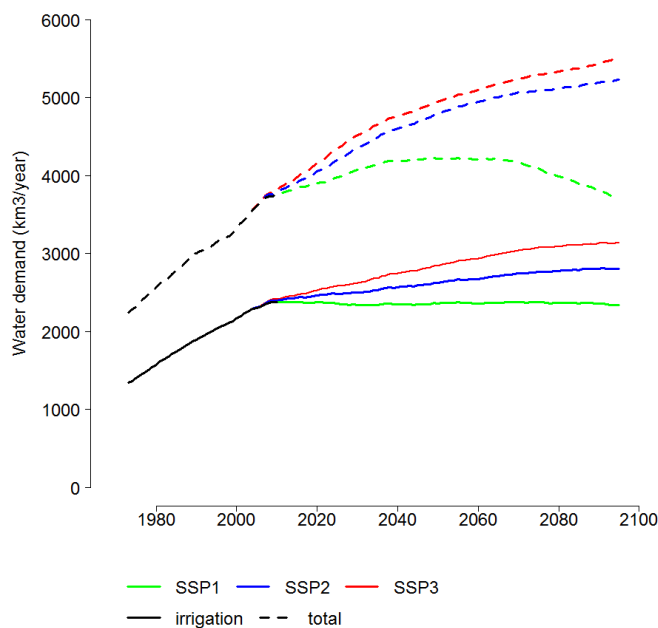
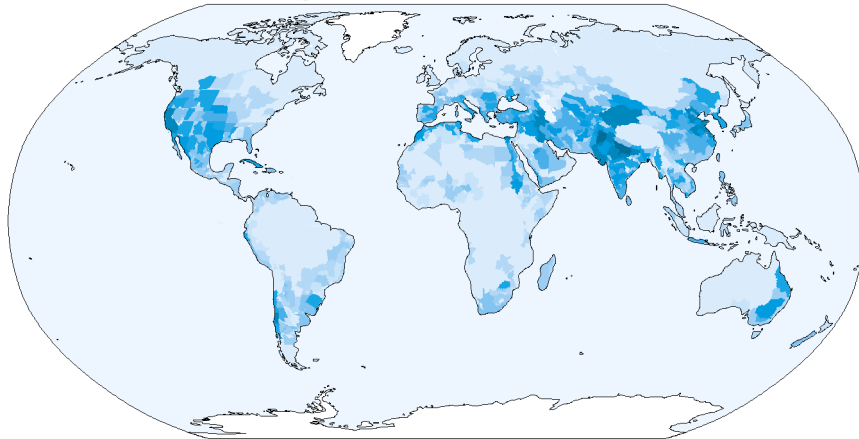


Figure 1. Change in global water demand for irrigation and total global water demand (also including that from industry, electricity generation and households) for different SSPs between 1980 and 2100. We used the combinations of SSP1 with RCP4.5, SSP2 with RCP6.0 and SSP3 with RCP8.5.

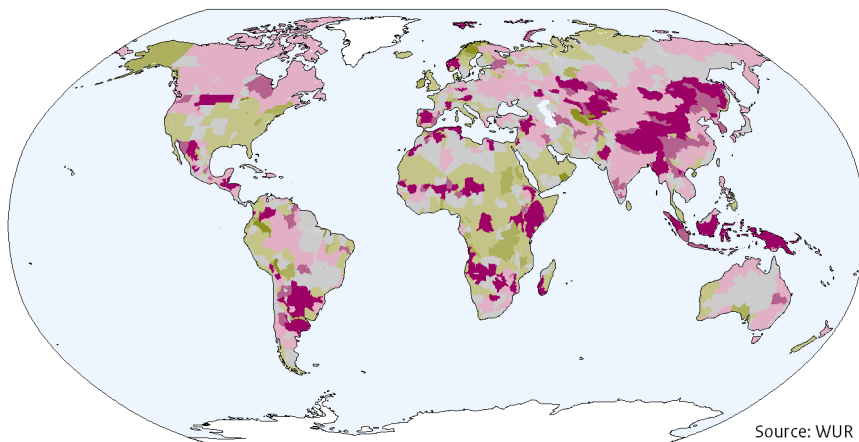
Figure 2 shows the spatial distribution of irrigation water demand in 2010 and the relative change in irrigation water demand between 2010 and 2050 at water province level for SSP2 with RCP6.0. The change pattern in Africa and Europe seems to be very scattered, with regions showing increases and decreases in demand, whereas there is a consistent increase in most parts of South Asia, China and Indonesia, where current irrigation demand is high already. This increase or decrease in irrigation water demand is the net result of climate change, change in irrigated area and projected irrigation efficiency improvements.

### Water demand for irrigation

Mean annual water demand for irrigation in 2010



Relative change in irrigation water demand in 2050



Source: WUR

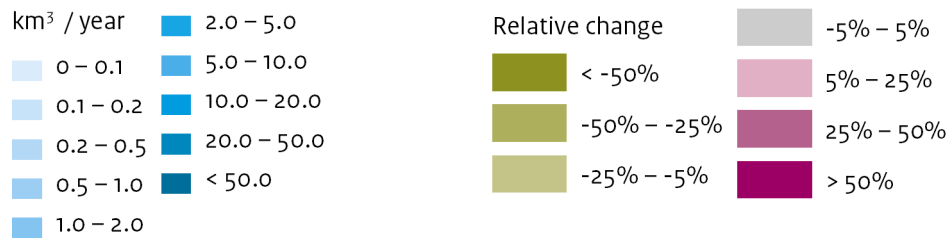
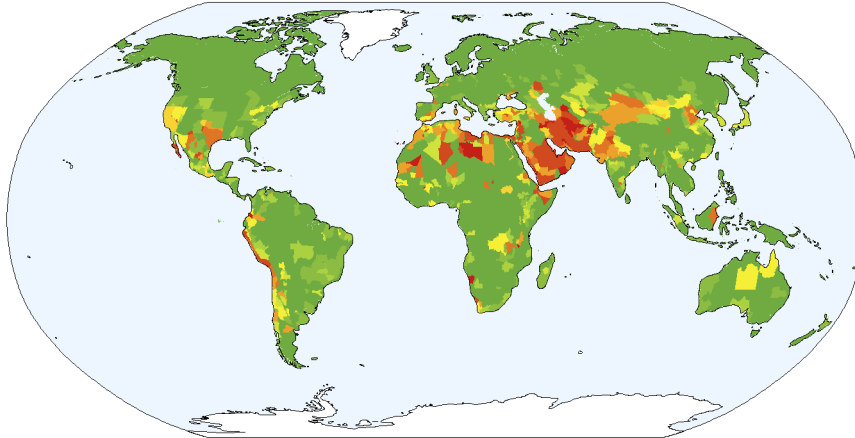


Figure 2. Present-day (2001–2010) mean annual water demand for irrigation per water province in  $10^6 \text{ km}^3 \text{ year}^{-1}$  and the relative change in irrigation water demand per water province in 2050 (future time slice 2046–2055) compared to present-day conditions for SSP2 with RCP6.0.

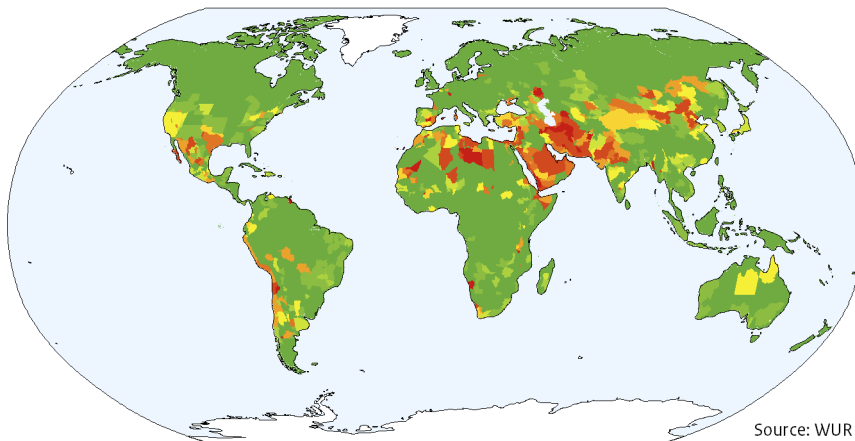
## Sources of water withdrawal

### Fraction of non-renewable water withdrawal needed to meet irrigation water demand

Fraction non-renewable in 2010



Fraction non-renewable in 2050



Source: WUR

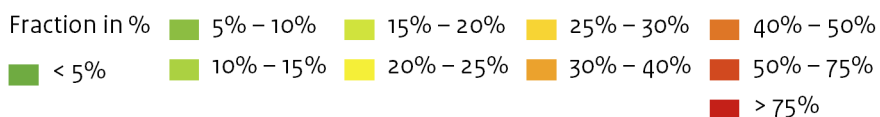


Figure 3. Fraction of non-renewable water withdrawal needed to meet irrigation water requirement in present-day and future situation (2050s SSP2 with RCP6.0). Note that this figure only includes irrigation water demand.

Figure 3 shows the fractions of non-renewable water withdrawals that are needed to fulfil the irrigation requirements. Non-renewable withdrawals are largest in the Middle East and North Africa, with around 75% of total withdrawals in some provinces, and the areas that depend on those water sources projected to expand in the future, due to climate change and an increasing demand for water. In the document on water scarcity related to groundwater, more information is presented on withdrawals of renewable and non-renewable water in different regions in the world. The information in that document stresses the high dependence of the Middle East and North Africa on non-renewable water and the relation with irrigation. The information also shows a decrease for this region of the irrigation demand and withdrawal of non-renewable water per capita due to an increase of irrigation efficiency and water availability.



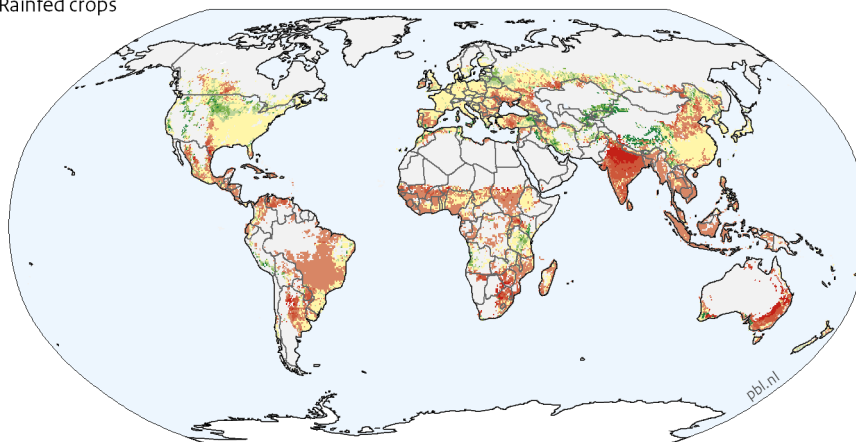
## FOOD

### Impact of climate change on food production

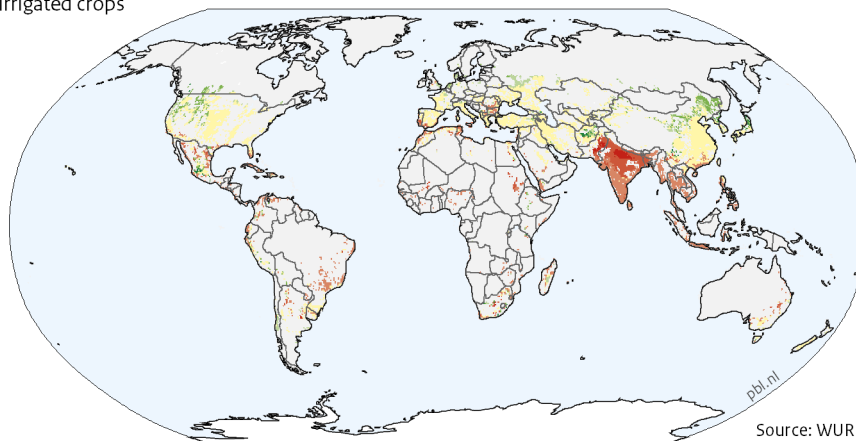
Isolating the impact of climate change on crop production, we can see an increase in crop production in some areas, but a decrease in others (Figure 4). In agreement with other studies, IMAGE results show that climate change will lead to a decrease in average crop yields in tropical and temperate regions, and to an increase in crop yields in northern regions where temperatures will become more favourable for agriculture. Projected crop yield decrease is largest in the Indo-Gangetic plains in Pakistan and India. Note that these reductions in yields will partly be compensated by an intensification of management, or a shift to different crop varieties that are more heat tolerant, but this is not included in the analysis presented here.

#### Projected relative change in average crop yields

Rainfed crops



Irrigated crops



Source: WUR

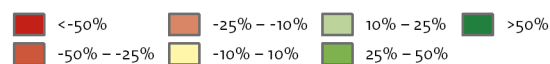


Figure 4. Projected relative change in average rainfed and irrigated crop yields in 2050 relative to 2010. The yield changes of individual crops are weighted according to their relative areas. Grid cells with cropped areas < 0.1% are masked.

## Water yield gaps

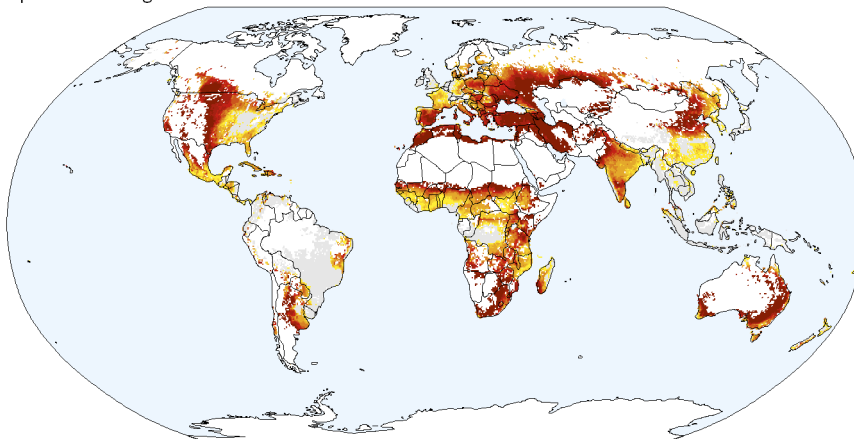
Figure 5 shows the water yield gaps for the 2050s (RCP6.0 with SSP2) for rainfed and irrigated agriculture. Those yield gaps are defined as the difference between actual (water limited) yield and potential yield (potential yield is the yield in the absence of water constraints):

- The irrigated yield gap is defined here as the difference between the yield constrained by water supply from renewable sources only and the potential yield in the absence of any water constraints.
- The rainfed yield gap is defined as the difference between the rainfed yields and the potential yield in the absence of any water constraints.

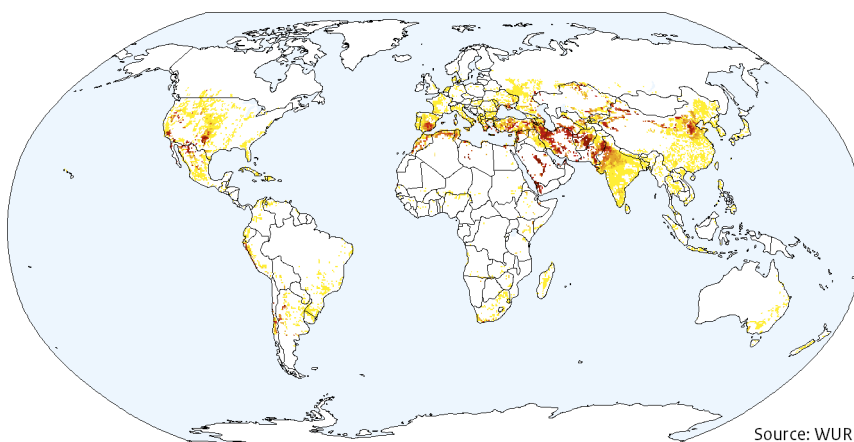
It is clear that the projected rainfed water gaps are larger than the projected irrigation water gaps, as irrigation closes part of the water yield gap. The Middle East, South Asia and Eastern China show the largest yield gaps in rainfed agriculture, but continue to have a large part of their agriculture under irrigation. However, there are also water yield gaps in irrigated agriculture, because part of the water demand might not be available, leading to a reduction in yields. Here, we assumed that only renewable water can be used for irrigation. As long as there will be access to additional non-renewable sources of water, the yield gap on irrigated land can be further reduced, but not in a sustainable manner.

### Projected water yield gap for agricultural areas in 2050

Gap for rainfed agriculture



Gap for irrigated agriculture



Source: WUR

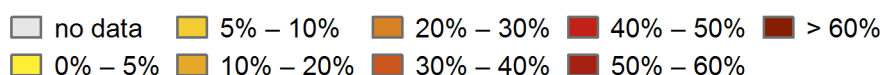


Figure 5. Projected water yield gap on rainfed and irrigated agricultural areas in 2050 (RCP6.0 with SSP2). The water yield gap is defined as the difference between actual yields and potential yield in the absence of water constraints.

## Crop producing areas of the world

Global distribution of total food and feed crop production , 2010

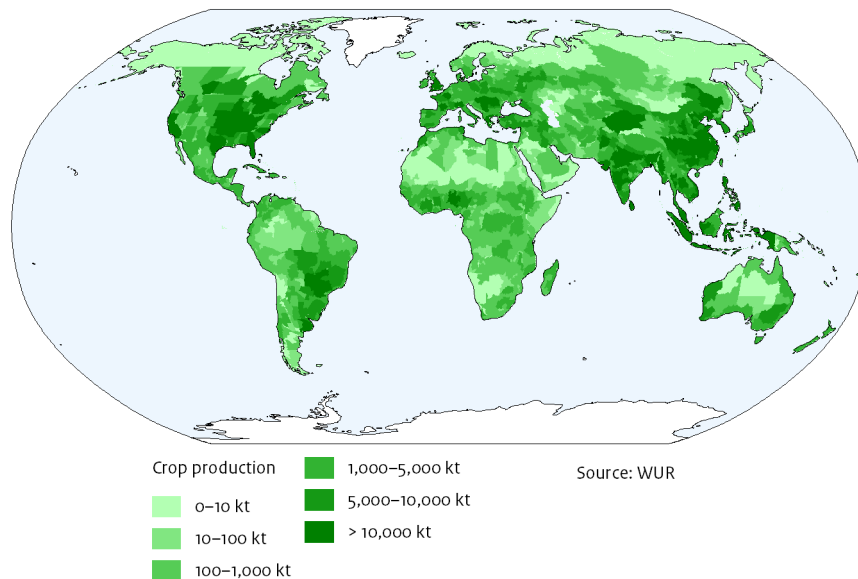


Figure 6. Global distribution of total (food and feed) crop production in tonne dry matter per year per water province.

Figure 6 shows the locations and production volumes of food and feed crops per water province. Although the sizes of the water provinces are unequal, this figure clearly shows where the global food and feed is produced. The western part of the United States, Europe and South and Southeast Asia are amongst the major producing areas of the world. In these regions, climate change affecting crop yields will have the largest impact on the total global crop production, and these regions are therefore particularly vulnerable from that perspective.

### Land expansion and abandonment

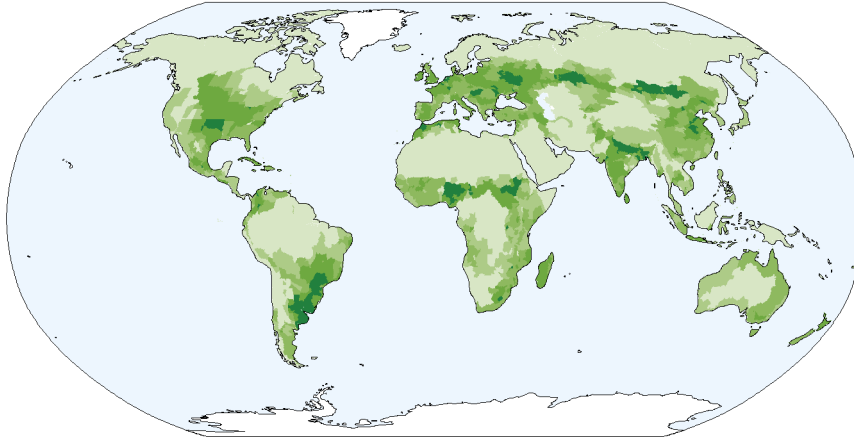
An intensification of agriculture on present-day cropland to increase crop yields is not sufficient to meet future food consumption. As shown in Figure 4, yield increase induced by agricultural intensification will partly be counteracted by climate change. In most parts of the world, additional land will be needed to meet the increasing demand. Figure 7 shows the current global distribution of cropland as a percentage of the total land area and the relative change in cropland according to IMAGE-LPJmL simulations for the SSP2-RCP6.0 scenario for the 2050s. Relatively large expansions of cropland are projected in South America, sub-Saharan Africa and South and Southeast Asia. At the same time, the projections show a decrease in cropland in parts of the United States and Europe. This can also be caused by an increase in imports from outside the region, leading to a decrease in local production of crops.

In areas where improved land, crop and water management cannot meet the growing food demand up to 2050, the area of cropland will increase at the expense of natural vegetation. This is the case in South and Southeast Asia, Central America, the eastern part of Brazil, and in sub-Saharan Africa, with arable land expansions of 20% to 50% (Van der Esch et al., 2017).

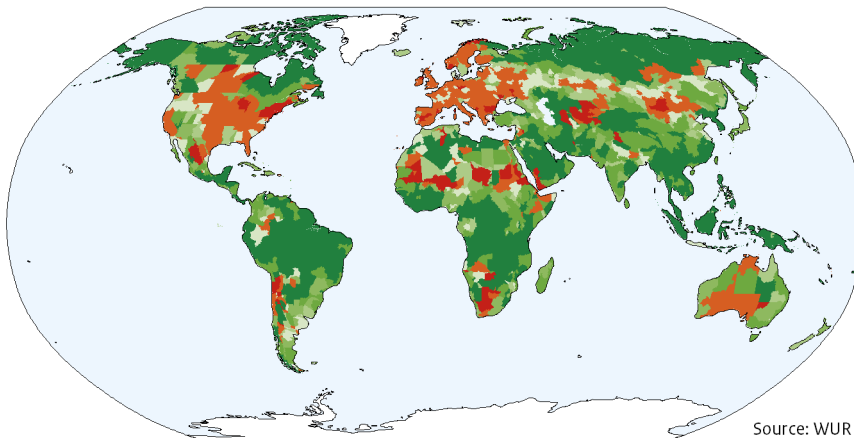
Figure 7 shows that a large part of the land area is already in use for agriculture in the United States, in Central and Southern Europe, and in South and Southeast Asia, indicating that land resources are already scarce there. These regions might therefore be vulnerable when climate change or water shortages lead to yield reductions.

**Cropland in percentage of total land area**

Percentage cropland in 2010



Relative change in cropland in 2050



Source: WUR

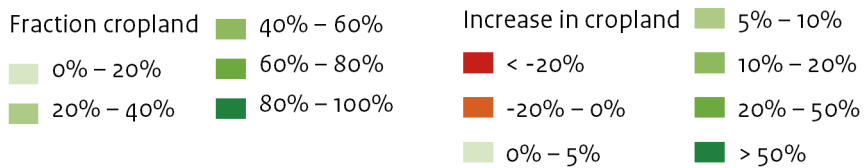
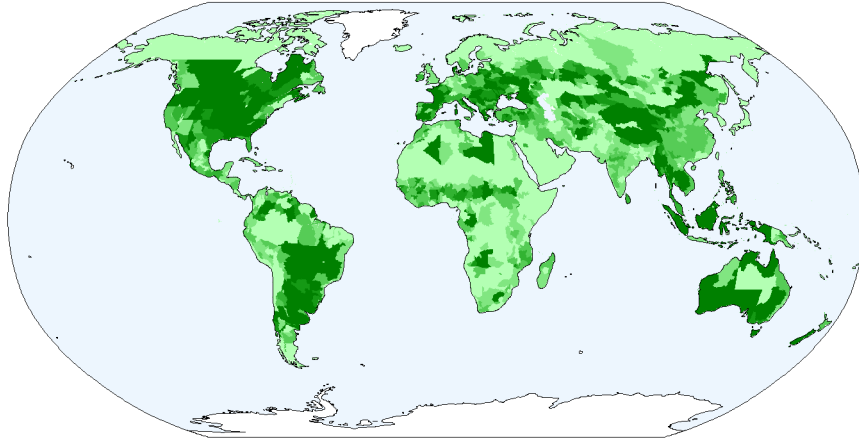


Figure 7. Present-day cropland as % of total land area, and the relative change in cropland between the present-day situation and the 2050s (SSP2 with RCP6.0).

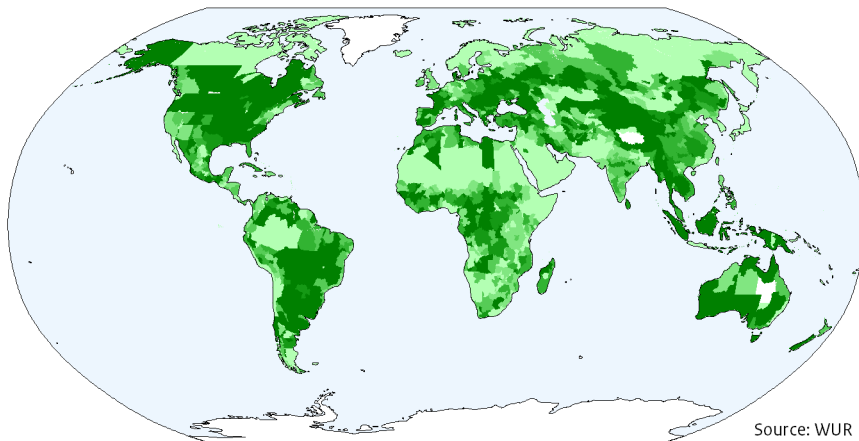
## Self-sufficiency

### Crop production per capita

2010



2050



Source: WUR

crop production per capita

0.0–0.2 tonnes	0.3–0.4 tonnes	0.5–0.6 tonnes	0.7–0.8 tonnes	0.9–1.0 tonnes	> 1.0 tonnes
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Figure 8. Present-day and future (2050: SSP2 with RCP6.0) per capita crop production per country (in tonne dry matter per year). Please note that this also includes crop production for livestock feed and for export.

Figure 8 shows the total annual production of food and feed crops per capita for current and future (SSP2-RCP6.0 scenario combination) conditions. This information is indicative of the self-sufficiency of the local population in growing its own food, although more information is required to really calculate food self-sufficiency. However, no information related to the import and export of crops is included, there is no data on per-capita food demand at country level, and no distinction is made between food crops and feed crops. The per-capita crop production currently required to meet global food demand is 0.47 tonnes dry matter per year, which is projected to increase to 0.56 tonnes by 2050 (for SSP2) due to dietary changes and increases in average per-capita food intake.

## Water demand: food versus nature

There is a strong competition between the water needed for food production and for aquatic ecosystems. A recent analysis shows that 41% of the global irrigation water withdrawals are actually needed to sustain the environmental flows. If these environmental flows would be respected, half of the globally irrigated croplands would see a production loss of > 10%, with losses of ~ 20% to 30% of the total national production levels in Central and South Asia. Major water efficiency improvements in both rainfed and irrigated agriculture could compensate for the negative impact on crop production (Figure 9) and eventually lead to a 10% net production gain, globally. If, however, the environmental flows would be fully respected in all regions, Northern India and Central Asia, especially, would experience a reduction in crop production of 20% to 30%, even with major improvements in rainfed and irrigation water management (Jägermeyr et al., 2017).

### Change in crop production constrained by environmental flow requirements

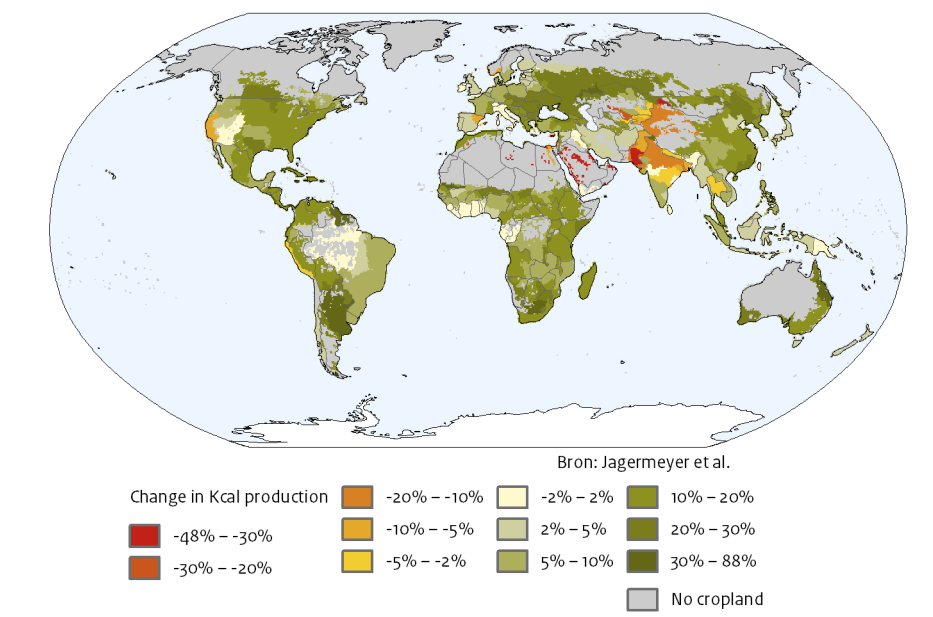


Figure 9. Environmental flows and water use for food production could be reconciled through effective water management. For the present-day situation (1980–2009), this map illustrated the change in total production with integrated water management constrained by environmental flow requirements, with respect to the current situation and aggregated to food production units (source: Jägermeyr et al., 2017).

### 1.1.5 Discussion

#### Uncertainties / Restrictions

IMAGE-LPJmL is a very strong tool to evaluate the interactions between climate, land and water resources and food production. The integrative character of the model enables capturing and quantifying feedbacks between climate change, land use, food production and water scarcity. However, there are some uncertainties and restrictions that need to be discussed.

In this study, we have not been able to use an ensemble of climate change scenarios to quantify the effects of uncertainty in climate change, as for example done for the water scarcity and flood risk hotspot analyses. This implies that only one General Circulation Model (GCM) pattern was used for estimating climate change, although the disagreement between models is still large, in some regions (IPCC, 2013). Although water withdrawal by other users could have been incorporated in IMAGE-LPJmL, this study does not include the competition between water users. For some regions, therefore, water availability in

agriculture might be slightly overestimated. This competition -present and future- is explicitly addressed in the study by Bijl et al. (2018).

Water quality is not included in the assessment, and therefore the impact of water quality on water availability for agriculture is not included. In some regions, water quality is too poor to be used for human consumption or irrigation.

In many food-producing areas of the world, agriculture is very intensive. In South Asia and China, for example, typically more than one crop per year is cultivated. This practice of double or triple cropping is not implemented in the current version of IMAGE-LPJmL, although it has a huge impact on both the quantity and the timing of irrigation water withdrawals (Biemans et al., 2016).

#### 1.1.6 Conclusion

Climate change, water availability and food production are intrinsically linked. Therefore, it is difficult to identify the hotspots of food production based on a single indicator, and we have presented several in this document. Based on a combination of the indicators presented in this document, a hotspot analysis can be made.

When comparing the various maps in this document, one region stands out. *South Asia* (India and Pakistan) is one of the main crop producing areas of the world (Figure 6). It has a very intensive agricultural system for which the production largely depends on irrigation. The water demand for irrigation is expected to increase further, despite increases in irrigation efficiency (Figure 2). However, a very large part of the water withdrawn for irrigation is being abstracted from a non-renewable source. This has already led to groundwater depletion, and for how much longer these withdrawals can continue is currently unknown. A substantial share of the irrigated production depends on this unsustainable supply of water. In addition, climate-change-induced temperature increases will lead to a strong decrease in agricultural production in this region, even if all the water required would be available (Figure 4). Cropland expansion to compensate for these losses will be difficult, as a large part of the available land is already being used as cropland. Pressure on land is therefore large (Figure 7). In fact, food production would drop even further, if environmental flow requirements would be respected (Figure 9).

Other hotspots include the western part of the United States, southern Africa and Australia, where a similar co-occurrence of climate change and increasing pressure on land and water will be experienced.

#### 1.1.7 Gaps and recommendations for future research

- Evaluate the effect of the large-scale implementation of climate change adaptation measures related to land and water. To what extent can the future yield gap be closed and the SDGs be achieved, given expected socio-economic developments and climate change (similar to Jägermeyr et al.)?
- Further investigate the emerging local conflicts between water users (including nature).
- Analyse the extent to which countries depend on the inflow of blue water from other countries.
- Improve the quantification of the links between climate, water and land.
- Improve the analysis of the effects of climate variability and the impact of extreme climate on vulnerability and stability.
- Conduct further in-depth analyses at higher resolution for the most important areas.

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