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THE IMPACT OF CLIMATE CHANGE
ON COSTS OF FOOD
AND PEOPLE EXPOSED TO HUNGER
AT SUBNATIONAL SCALE

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Abstract

Climate change and socioeconomic developments will have a decisive impact on people exposed to hunger. This study analyses climate change impacts on agriculture and potential implications for the occurrence of hunger under different socioeconomic scenarios for 2030, focusing on the world regions most affected by poverty today: the Middle East and North Africa, South Asia, and Sub-Saharan Africa. We use a spatially explicit, agro-economic land-use model to assess agricultural vulnerability to climate change. The aims of our study are to provide spatially explicit projections of climate change impacts on Costs of Food, and to combine them with spatially explicit hunger projections for the year 2030, both under a poverty, as well as a prosperity scenario.

Our model results indicate that while average yields decrease with climate change in all focus regions, the impact on the Costs of Food is very diverse. Costs of Food increase most in the Middle East and North Africa, where available agricultural land is already fully utilized and options to import food are limited. The increase is least in Sub-Saharan Africa, since production there can be shifted to areas which are only marginally affected by climate change and imports from other regions increase. South Asia and Sub-Saharan Africa can partly adapt to climate change, in our model, by modifying trade and expanding agricultural land. In the Middle East and North Africa, almost the entire population is affected by increasing Costs of Food, but the share of people vulnerable to hunger is relatively low, due to relatively strong economic development in these projections. In Sub-Saharan Africa, the Vulnerability to Hunger will persist, but increases in Costs of Food are moderate. While in South Asia a high share of the population suffers from increases in Costs of Food and is exposed to hunger, only a negligible number of people will be exposed at extreme levels. Independent of the region, the impacts of climate change are less severe in a richer and more globalized world.

Adverse climate impacts on the Costs of Food could be moderated by promoting technological progress in agriculture. Improving market access would be advantageous for farmers, providing the opportunity to profitably increase production in the Middle East and North Africa as well as in South Asia, but may lead to increasing Costs of Food for consumers.

In the long-term perspective until 2080, the consequences of climate change will become even more severe: while in 2030 56% of the global population may face increasing Costs of Food in a poor and fragmented world, in 2080 the proportion will rise to 73%.

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1 Introduction

A comprehensive understanding of climate change impacts requires extending the research beyond the physical properties of the climate system to human impacts and the geographic and socioeconomic factors that influence them (Wheeler, 2011). Several studies warn that climate-related reductions in global food production in combination with increasing food demand due to population and income growth will lead to increased prices of food (Nelson et al., 2009; Willenrockel, 2011). For example, Parry et al. (2005) projects that global cereal prices could increase by 30-70% by 2050 and more than 160% by 2080. Such rising prices also increase the risk of hunger, as food consumption becomes more expensive. While rising prices also have the potential to increase the income of people working in agriculture, the net effects are most often negative. The poorest 20% of the population often receive parts of their income from agriculture, but are still net food-buyers, while net food-producers can rather be found in middle income segments (FAO, 2011; Ivanic and Martin, 2008). (Parry et al., 2009) estimate that a combination of climate change, high population growth and increasing regional income disparities could increase the number of people at risk of hunger worldwide by up to 20% by 2050. However, it remains uncertain, how the regional and local distribution of these effects may be.

The aims of our study are therefore: to provide spatially explicit projections of climate change impacts on Costs of Food, an indicator defined as the average production Costs of Food and feed crops in a specific spatial area. We estimate this indicator using the Model of Agricultural Production and its Impact on the Environment (MAGPIE) (Biewald et al., 2014; Lotze-Campen et al., 2008; Schmitz et al., 2012), a spatially explicit agro-economic land use model. This indicator is combined with spatially explicit hunger projections for the year 2030, in order to develop an Agricultural Vulnerability Indicator. We analyze the latter under two different socioeconomic scenarios, one of poverty and one of prosperity.

This report is structured as follows. First, we present a literature review on other studies investigating the effects of climate-induced yield changes on poverty. We describe how our study extends previous analyses and the scope and limitations of our approach. Then, we introduce the methodology, indicators and scenarios that we use in this study. Third, we present results and discuss their implications, followed by the conclusions and policy implications in the last chapter.

1.1 Other studies modelling climate change impacts on agricultural production and poverty

One of the most important impact chains through which climate change affects the risk of hunger is the change of potential crop yields. Changed precipitation and temperature will alter the global patterns of potential yields, and alter the allocation of crop production as well as the production costs. This will in turn change market prices, affect households economic situation and finally poverty levels and the risk of hunger. This impact chain has been explored to various degrees in the literature, while some studies were modelling the whole impact chain from climate to hunger, others focused only on parts of it.

Among the first studies analyzing this chain has been Tobey et al. (1992), using an economic model to analyze yield shocks in agriculture. Their results show that food markets can effectively dampen such shocks through adapted production and consumption.

While Tobey et al. (1992) only simulated parts of the impact chain, Parry et al. (2005) analyzed the whole impact chain, feeding climate simulation results into process-based crop models, which in turn informed an economic model that estimated the market outcomes on supply and demand. The economic model also provides a simple indicator for the risk of hunger. The study concludes that in a scenario with high climate impacts and little adaptive capacity, Africa will be the world region at the greatest risk of hunger. Similar results are reported by Parry et al. (2009). By 2050, the semi-arid regions north and south of the equator in Africa will be especially vulnerable since the projected increased aridity is expected to overlap with low income levels of the local population. Additionally,

the poorest parts of South and South-East Asia are likely to be substantially affected by climate change. Hasegawa et al. (2014), use a similar methodology, and argue that population and economic development have a greater impact on the risk of hunger than negative climatic conditions as such. The impact on the risk of hunger varies across regions not only as a result of different climatic conditions but also due to a different calorie intake and agricultural land availability.

The agricultural model intercomparison project (AgMIP) uses 2 climate models, 5 crop models and nine global economic models to explore the impact chain from climate change to market outcomes. In the year 2050, the climate impacts of a very high emission scenario (RCP8.5) resulted – in the average of all simulations - in the reduction of average potential yields by 17%, an area increase by 11%, a reduction in consumption by 3% and a price increase by 20% (Nelson et al., 2014). An update of this study focused on more likely medium and high emission scenarios (RCP4.5 and RCP6.0), resulting in much lower climate impacts, approximately halving the yield and price impacts (Wiebe et al., accepted). Climate impacts may be even lower if CO₂ fertilization effects would be included, which are still excluded in most analysis due to the high uncertainty of the effect. Poverty and undernutrition impacts were not analyzed.

Ahmed et al. (2009) extend previous studies by having a more detailed representation of market impacts on poverty, combining an economic model with a poverty module. This module utilizes micro-simulation for representative households at the poverty line in each socioeconomic stratum to determine changes in poverty headcount based on changes in real income. They quantify the vulnerability of the poor to potential changes in climate volatility, in the context of the frequency and magnitude of different climate extremes. The authors use again a scenario with strong climate impacts and low adaptive capacity to analyze agricultural productivity changes in the period 2017 to 2100 in 16 developing countries. In their study the effects of climate shocks are visible through two channels: changes in earnings and changes in the real costs of living at the poverty line. The results show that the highest shares of population entering poverty as a consequence of climate extremes are in Bangladesh, Mexico and in the south-west of Africa. The urban labor group appeared to be the most vulnerable to extreme climate events and to any resulting food price increases. Agricultural households on the other hand were much less exposed.

Using a similar approach, Hertel et al. (2010) use disaggregated data on household economic activity within individual countries and embed this data within the General Equilibrium model to explore the impacts on poverty of changes in agricultural productivity due to climate change in the period 2000-2030. The authors compare a low agricultural productivity scenario in a world of rapid temperature changes, with a high productivity scenario without temperature increase. Here, by 2030 the poorest countries are the ones hit hardest by the agricultural productivity changes, since their economies are more dependent on agricultural production. The model results show that the highest negative impacts of climate change on crops are in Sub-Saharan Africa, but high losses also occurred in the US and China. Household survey data from 15 developing countries were then used to estimate the impact of agricultural price changes of welfare on different groups of poor households. The authors find that global cereal prices increase by 32% in the low productivity scenario and 16% in the more optimistic productivity scenario. In the low productivity scenario, poverty increased by as much as one-third in the urban labor social strata in Malawi, Uganda, Zambia and in the non-agricultural self-employed stratum in Bangladesh.

1.2 Scope and limitations

Similar to Parry et al. (2005), Hasegawa et al. (2014), Ahmed et al. (2009), Hertel et al. (2010) and Nelson et al. (2013), we use climate projections to determine future crop yield potentials under climate change, which in turn inform an economic model that estimates the climate impacts on production costs. While other studies (Ahmed et al., 2009; Hasegawa et al., 2014; Hertel et al., 2010,

Ivanic and Martin, 2008) try to translate economic impacts into indicators of poverty or food security (e.g. population exposed to undernutrition or risk of hunger), our approach does not explicitly model the impact chain that leads from market outcomes to poverty. Instead, the major strength of this analysis is to observe the effects of climate change on a much finer scale (0.5°) than other global models, which usually operate on a national or (world)-regional scale. To investigate the impacts of global environmental changes on poverty in specific locations, different research methods have to be used. This report proposes a new approach. We combine model-based global agricultural indicator projections that are available at the 0.5° grid cell level population and hunger projections at the same resolution in order to identify overlaps between the areas with the highest climate change impacts on agricultural production and the areas that are projected to be most prone to the risk of hunger. We use the spatially explicit hunger index instead of poverty indicators, since such indicators such as the frequently used ratio of population living below the poverty line are mostly provided on regional level. Our study places a special emphasis on modelling on a high spatial resolution, since recent trend analysis shows that poverty will be increasingly concentrated in particular areas in the future (Shepherd et al., 2013). For example, Amarasinghe et al. (2005) show that in Sri Lanka the poorest households are located in dry areas where small-size agricultural holdings depend on rainfed production and where income diversification opportunities are scarce due to a long distance to the next urban infrastructure. Furthermore, the urban poor as the net buyers of food are particularly vulnerable to food price spikes that often follow climate induced production shocks and declines (Hein et al., 2009; McMichael et al., 2012; Smit and Parnell, 2012). Barrett et al. (2006) point out that it is important to identify such less-favored areas. They need more direct interventions for improving the capability of households to build and protect their assets and to improve their access to financial services. The most appropriate interventions will depend on the local context. The ability of households in such locations to cope with shocks and disasters will be particularly challenged. The inadequate capacity of households to recover from such shocks can lead to a cycle of losses and maladaptive strategies including divestment of productive assets such as livestock and selling land for food (UNDP, 2007).

Our study focuses on the long-term effects of climate change through crop yields on agriculture, and does not account for climate impacts through other impact chains, like extreme events and disasters (Shepherd and et al., 2013), unforeseen climate shifts (FAO, 2013), negative impacts on human capital (Behrman, J. et al., 2004; Clarke and Hill, 2013; Foster and Rosenzweig, 1993; Glick and Sahn, 1998; Hoddinott, 2006) or physical capital (Carter et al., 2007) employed in agriculture.

2 Methods

2.1 Models

The methodological cornerstone of our study is the coupled model system of the biophysical crop model LPJmL and the spatially explicit agroeconomic land use model MAGPIE.

2.1.1 The biophysical crop model LPJmL

LPJmL simulates carbon and water cycles as well as vegetation growth dynamics depending on daily climatic conditions and soil texture. Natural vegetation is represented in LPJmL at the biome level by nine Plant Functional Types (PFTs) (Sitch et al., 2003). The model calculates closed balances of carbon fluxes (gross primary production, auto- and heterotrophic respiration) and pools (in leaves, sapwood, heartwood, storage organs, roots, litter and soil), as well as water fluxes (interception, evaporation, transpiration, snowmelt, runoff, discharge) (Gerten et al., 2004; Rost et al., 2008). Photosynthesis is

simulated following the Farquhar model approach (Farquhar et al., 1980). Processes of carbon assimilation and water consumption are parameterized on the leaf level and scaled to the ecosystem level. Carbon and water dynamics are closely linked so that the effects of changing temperatures, declining water availability and rising CO₂ concentrations are accounted for and their net effect can be evaluated (Gerten et al., 2004, 2007). Physiological and structural plant responses determine water requirements and consumption.

Competition between PFTs due to differences in their performance under given climate conditions, can lead to changes in vegetation composition as less adapted PFTs can be out-competed and replaced. Subsequently to alterations in vegetation composition, i.e. in the PFT distribution, changes in productivity and respective carbon fluxes can also be quantified. This applies to long-term climate trends as well as interannual climate variability, including the impacts of extreme events. Therefore, the LPJmL model is indeed capable of capturing dynamic responses to, e.g., single or consecutive drought events. The suitability of the LPJmL framework for vegetation and water studies has been demonstrated by validating simulated phenology (Bondeau et al., 2007), river discharge (Gerten et al., 2004; Biemans et al., 2009), soil moisture (Wagner et al., 2003) and evapotranspiration (Sitch et al., 2003; Gerten et al., 2004).

2.1.2 The agroeconomic land use model MAgPIE

MAgPIE (Model of Agricultural Production and its Impact on the Environment) is a global, spatially explicit, economic land use model solving in a recursive-dynamic mode (Biewald et al., 2014; Lotze-Campen et al., 2008; Schmitz et al., 2012). The model distinguishes ten world regions on the demand side (Figure 1) and uses input data of 0.5 degree resolution on the supply side. Due to computational constraints, all model inputs on the supply side are aggregated to clusters for the optimization process based on a k-means clustering algorithm (Dietrich et al., 2013). With income and population projections (see section 2.3.1) as exogenous inputs, demand for agricultural commodities is projected in the future and produced by 15 food crops, 5 livestock products, 1 fiber crop, and by fodder as an intermediate input. While demand is scenario-specific and changes over time, it does not react to changes in supply or any other variables at each time step. Feed requirements for livestock production activities consist of a mixture of grazed biomass from pastures as well as fodder and food crops. The livestock-specific feed energy requirements depend on biological needs for maintenance and growth but also temperature effects and the use of extra energy for grazing (Wirsenius, 2000). The model simulates time steps of 10 years and uses in each period the optimal land-use pattern from the previous period as initial condition.

On the biophysical side, the model is linked to the grid-based dynamic vegetation model LPJmL which provides important biophysical inputs like crop yields under both rainfed and irrigated conditions, related irrigation water demand per crop, and water availability depending on climatic conditions on a 0.5 degree resolution. Spatially explicit land types in MAgPIE comprise cropland, pasture, forest, urban areas, and other land (Krause et al., 2013). The objective function of MAgPIE minimizes global agricultural production costs, which involves factor costs for labor, capital, and intermediate inputs derived from the GTAP database (Narayanan and Walmsley, 2008), investments into research and development (R&D), land expansion costs as well as trade and transport costs. R&D investments allow MAgPIE to increase crop yields in a particular region. This endogenous implementation of technical change is based on a surrogate measure for agricultural land use intensity (Dietrich et al., 2014). Expansion of cropland is the alternative to increase the production level. Expansion involves land conversion costs for every unit of converted land, which account for the preparation of new land and basic infrastructure investments (Krause et al., 2013). Land conversion costs are based on country-level marginal access costs generated by the Global Timber Model (GTM) (Sohngen et al., 2009).

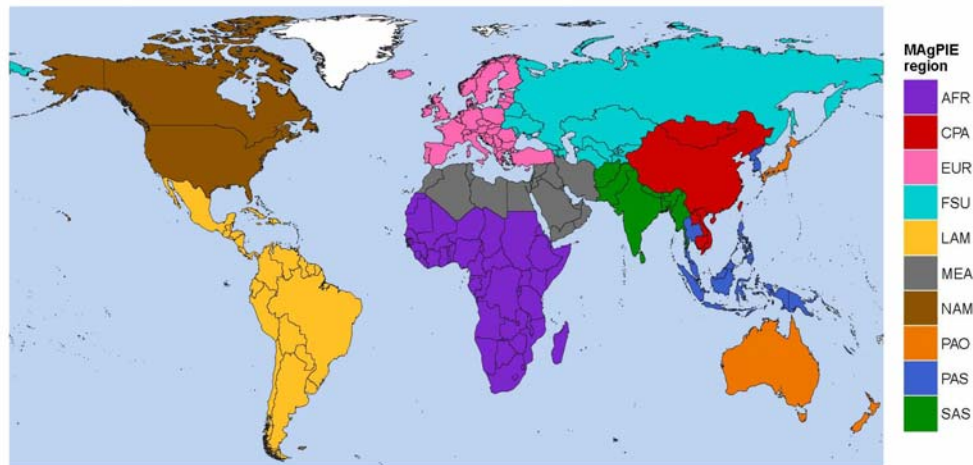


Figure 1: The ten world regions in MAGPIE: AFR = Sub-Saharan Africa, CPA = Centrally Planned Asia (incl. China), EUR = Europe (incl. Turkey), FSU = Former Soviet Union, LAM = Latin America, MEA = Middle East and North Africa, NAM = North America, PAO = Pacific OECD, PAS = Pacific Asia, SAS = South Asia (incl. India).

International trade in MAGPIE is implemented by using flexible minimum self-sufficiency ratios at the regional level. Self-sufficiency ratios describe how much of the regional agricultural demand quantity has to be produced within a region. For instance, a ratio for cereals of 0.8 means that 80% of cereals are produced domestically, whereas 20% are imported. To represent the trade situation of 1995, we calculated the self-sufficiency ratios for each region and commodity based on FAO data. There are two virtual trading pools which allocate the global demand to the different supply regions. The demand which enters the first pool is allocated according to fixed criteria. Self-sufficiency ratios determine how much is produced domestically, and export shares determine the share of each region in global exports. The export shares are generated for every crop for the year 1995 and are taken from FAO data as well (Schmitz et al., 2012).

However, although the initial self-sufficiencies for this pool stay constant over time, the final self-sufficiencies do change since domestic demand and population change over time. The demand which enters the second pool is allocated according to comparative advantage criteria to the supply regions. The criteria are biophysical yield, production costs and costs of intensification through investment in yield-increasing technological change. This implies that the model minimizes global production costs and produces in those cells where it is most economical compared to other cells.

When analyzing model-based changes of spatial production patterns and production costs, as done in this study, the following model-inherent mechanisms should be considered:

- 1.) Notwithstanding the negative impacts of climate change on agriculture, a region and scenario-specific number of people has to be fed. There are two model-inherent adaptation mechanisms to compensate for decreases in yields and water availability: 1. More imports, compensating decreases in domestic production, 2. Stabilization of regional production through expanding agricultural area, investing in yield-increasing technical change, or investing in irrigation infrastructure.
- 2.) The possibility of using trade as a measure to alleviate the impacts of climate change is limited in a scenario with high trade barriers. A globalized world is better able to compensate locally heterogeneous impacts on yields through adjusting trade flows.

- 3.) Climate change can lead to lower yields as well as altered water availability. Lower availability of water reduces irrigated production with higher yields compared to the case of no climate change, but also reduces the possibility of expanding irrigated crop area.

2.2 Developing the Agricultural Vulnerability Indicator

In order to estimate the agricultural vulnerability of poor people related to climate change, we combine the Vulnerability to Hunger Index with Costs of Food as a socioeconomic agricultural indicator. In the following two sections we describe 1. the methodology behind the spatially explicit Vulnerability to Hunger Index and its future projection and, 2. the model-based agricultural indicator Costs of Food. Since it is not only important to know where people are vulnerable, but also how many, we describe in the last part a spatially explicit data set on population which we can use to estimate the number of people impacted.

2.2.1 Spatially explicit Vulnerability to Hunger Index

For the Global Hunger Index described in the publication by von Grebmer et al. (2011) from the International Food Policy Research Institute (IFPRI), three equally weighted indicators are combined in one index, namely the proportion of people who are undernourished, the prevalence of underweight in children younger than five and the mortality rate of children younger than five. All three index components are expressed in percentages and weighted equally. Higher Global Hunger Index values indicate more hunger, lower values indicate less. Of the three components mentioned above, only child underweight and child mortality are provided on grid cell level for the years 1998-2002 and 2000, respectively (Center for International Earth Science Information Network - CIESIN - Columbia University, 2005a, 2005b). The Food and Agriculture Organization of the United Nations (FAO) provides data on prevalence of stunting among children under five for a resolution of 5 arc-minutes for varying years before 2007 (FAO, 2014), which we use as a replacement for the non-spatially explicit undernourishment indicator of the Global Hunger Index. Based on these three spatial data sets (child underweight, child mortality and stunting among children below five), we derive the spatially explicit Vulnerability to Hunger Index used in this study according to the above-mentioned method of IFPRI. Due to the lack of the availability of a spatially explicit data set representing the entire population, the Vulnerability to Hunger Index pertains now only to children. In order to be comparable to other studies, we use the hunger level categories defined by von Grebmer et al. 2011 (Table 1). We use the term Vulnerability to Hunger because it reflects whether people possess sufficient money to afford the necessary food to avoid suffering from hunger. The Vulnerability to Hunger Index is projected based on economic poverty data, thus representing changes in income. Changes on the supply side through climate impacts are represented through the Costs of Food, discussed and explained below.

Table 1: Categories for the Vulnerability to Hunger index defined by von Grebmer et al. (2011). The index ranks spatial units on a 100-point scale. Zero is the best score (no hunger), and 100 is the worst. Neither of the two extremes is reached in practice.

Description hunger level	Abbreviations used in graphs	Classifications
extremely alarming	EA	≥ 30.0
alarming	A	20-29.9
serious	S	10-19.9
moderate	M	5-9.9
low	L	≤ 4.9

In a second step, we project the Vulnerability to Hunger Index for the year 2000 to the year 2030 using scenario-based national poverty projections provided by the World Bank (Rozenberg and Hallegatte,

2015). While the Vulnerability to Hunger Index has a spatial resolution of 0.5°, the poverty projections are on a country basis. We therefore assume that the subnational pattern of the Vulnerability to Hunger Index stays constant over time and thereby neglect that the spatial distribution of economic prosperity and failure might change over time.

Of the data sets provided by the World Bank, the following are correlated to the national averages of the Vulnerability to Hunger Index in a meaningful way: poverty gap referring to the 1.25 US\$ poverty line (povgap) with $R^2 = 0.32$, percentage of people living on less than 1.25 US\$ a day (poor) with $R^2 = 0.51$, percentage of people living on less than 4\$ a day (nearpoor) with $R^2 = 0.67$. The combined data sets are correlated to the Vulnerability to Hunger Index with $R^2 = 0.70$. Based on these relations, we created a linear regression with several variables which resulted in a function depicting the relation between the national values for the Vulnerability to Hunger Index in 2000 and the different poverty indicators:

$$\text{Vulnerability to Hunger Index} = 4.237 + (-52.899 * \text{povgap} + 38.285 * \text{poor} + 16.151 * \text{nearpoor})$$

We use this function then again for the year 2030 to translate national values of the poverty indicators into national values of the Vulnerability to Hunger Index. Assuming that the spatial distribution of the Vulnerability to Hunger Index has not changed over time, we distribute the projected values of the Vulnerability to Hunger Index according to the original spatial distribution (Figure 16 in the Appendix shows the correlation between the fitted and the original values).

We substituted missing data of the poverty indicators by creating a list of countries sorted by the national averages based on the Vulnerability to Hunger Index. Based on the linear regression described in the previous section, each average Vulnerability to Hunger Index value was then paired with the respective poverty value (poor, nearpoor, povgap) for the year 2000. For countries without these poverty values, we used a weighted mean of the two poverty indicators of the countries closest to the country without value in the ordered list. Furthermore, new values for 2000 were projected to 2030 as described above. Figure 2 displays the resulting distribution of the completed Vulnerability to Hunger Index for the present.

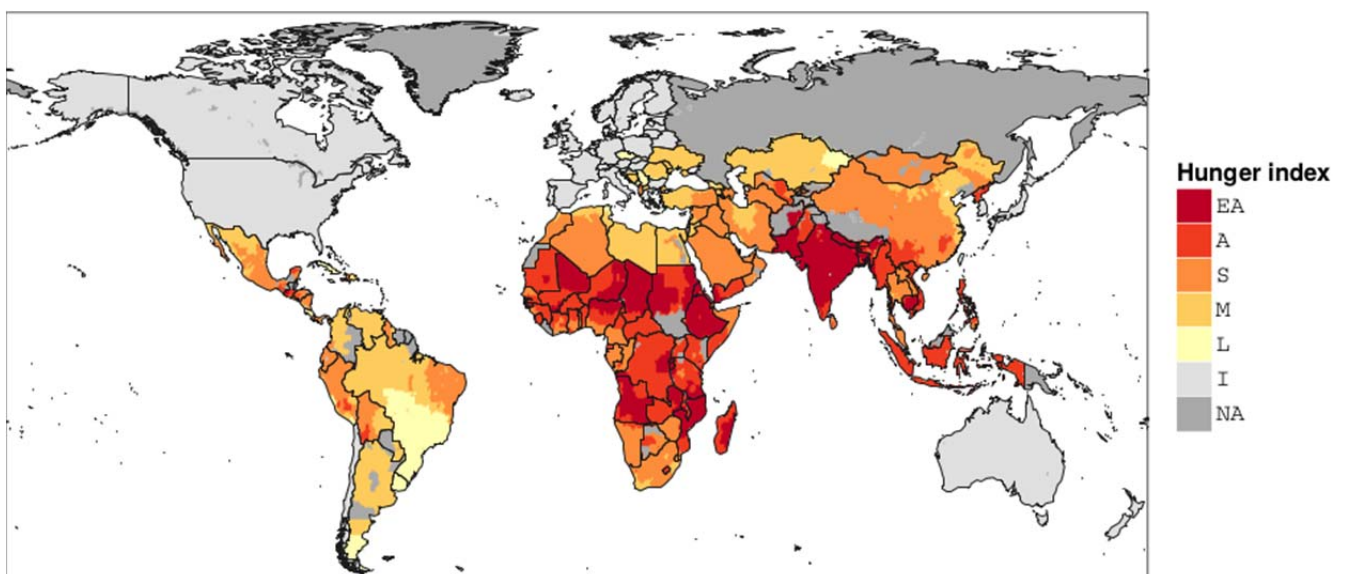


Figure 2: Vulnerability to Hunger Index based on child undernourishment, child underweight and child mortality rate. The CIESIN data on child underweight and child mortality rate reflect data from 2004-2011. The child undernourishment data from the FAO are assembled from varying years. Light grey indicates industrial countries (I), dark grey reflects that no data are available nor can be deducted (NA). (Hunger levels: EA = extremely alarming, A = alarming, S = serious, M = moderate, L = low.)

Finally, the Vulnerability to Hunger Index will be combined with Costs of Food from the MAgPIE model (see section 2.2.2 for an explanation) in order to be able to show not only where people relying on agricultural production are most affected by climate change impacts, but also where people exposed to hunger are most affected.

2.2.2 The agricultural indicators: Yields, production and Costs of Food

In order to see how climate change can impact farmers in poor regions, we identified three relevant indicators for agriculture which are sensitive to climate change, namely crop yields, crop production, and Costs of Food. While yields are simulated with the biophysical model LPJmL, production and Costs of Food are generated with the agro-economic model MAgPIE. They are based on an aggregate of food crops which include¹: temperate cereals (wheat, barley, rye, mixed grain, oats, triticale), maize, tropical cereals (millet, sorghum, canary seed, fonio, quinoa), rice, soybean, rapeseed (rapeseed and mustard seed), groundnut, sunflower, oilpalm, pulses (bambara beans, beans dry, broad beans dry, chick peas, cow pea dry, lentils, lupins, peas dry, pigeon peas, other pulses, vetches), potato, cassava, sugar cane, sugar beet and others (vegetables and fruits).

Potential crop yields are generated with the biophysical model LPJmL and show how a changing climate impacts agricultural yields. Yields shown are the area-weighted average of irrigated and rainfed yields, before economic interventions such as changes in land management or technology. Therefore, these results do not necessarily reveal information on changes in production levels. The values of the indicator are presented in giga joule (GJ) per hectare (ha) for each 0.5° grid cell. We show joule rather than tonne in order to provide a comparable unit across different crops.

Availability of irrigation water is in some parts of the world an important precondition for agricultural production. Since irrigation depends on biophysical conditions such as vegetation cover, as well as climatic conditions such as precipitation, it is also sensitive to climate change. The biophysical water availability discussed in section 3.1 does not represent irrigation water availability. In order to account for non-agricultural water use and minimum environmental flows, the adequate amount of water is deducted from the total available water in rivers, lakes and wetlands.

The Costs of Food are the aggregated costs for the production of food and feed crops per GJ for each 0.5° grid cell. Feed production costs are included because food and feed crops are (in the model and mostly in reality) identical, the costs for production are therefore the same. Production costs for bioenergy or fiber are not included. The costs include land conversion costs, transport costs, factor requirements, investments in irrigation infrastructure, and agricultural R&D investments. Regional R&D investments are spatially distributed according to production patterns. Although it is not possible to derive direct consumer prices as a result of the interplay between demand and supply at the grid level, the changes in aggregated production costs can be interpreted as changes in prices, if we assume that there is a constant mark up (profit margin) for the analyzed food crops. Since Costs of Food are directly influenced by climate impacts on yields, they are a good indicator for our study. Since agricultural R&D investments are included in Costs of Food, they cannot be interpreted completely as private marginal costs faced by a farmer, since a part of the costs are paid on the national level, e.g. by tax payers, or on the global level by aid foundations. The Costs of Food are presented in US\$/GJ for each 0.5° grid cell².

2.2.3 Spatially explicit population

In order to estimate climate change impacts on poverty, it is decisive to know how many people are affected by these impacts. Therefore a dataset of population density on a 0.5° grid for the year 2005 is used (Center for International Earth Science Information Network (CIESIN), Centro Internacional de

¹ The crops in brackets explain the crop groups used in MAgPIE.

² To give an example, one dry matter tonne of cereals corresponds to approximately 17.9 GJ.

Agricultura Tropical (CIAT), 2005). In order to project the gridded population into the future, we use the population scenarios developed for the different Shared Socioeconomic Pathways (SSPs) (International Institute for Applied Systems Analysis (IIASA), 2013). Due to a lack of better data, we assumed that the distribution of people in each country stays the same, but that population size changes in each grid cell proportionally to the change of population in the entire country. The maps showing the population projections can be found in the Appendix (Figure 17).

2.3 Scenarios

2.3.1 Socioeconomic scenarios

In order to analyze how people exposed to hunger are affected by climate change in different future socioeconomic settings, we use two extreme scenarios based on economic developments. On the one hand a scenario of prosperity, representing a future world with high GDP and low population growth, and on the other hand a scenario of poverty where GDP growth is low and population growth is high.

We base key indicators of these scenarios on the SSPs, which have been developed by the different key climate research communities in order to be able to explore the long-term consequences of anthropogenic climate change and possible responses (Kriegler et al., 2014; Moss et al., 2010; Nakicenovic et al., 2014; O'Neill et al., 2014; van Vuuren et al., 2012). The relevant indicators of the poverty scenario are based on SSP4, the relevant indicators for the prosperity scenario are based on SSP5. The qualitative indicators defined for each SSP have to be translated into quantitative model input for the agro-economic model MAGPIE, including trends in environmental awareness, globalization and technological change. The quantitative data for these scenarios (population and GDP growth) have been made publicly available by the International Institute for Applied Systems Analysis (2013).

In the context of agro-economic modeling, population scenarios translate into overall demand for crop and livestock products, while the region-specific development of GDP influences dietary habits such as consumption of livestock-related products and the amount of calories consumed, or calories wasted per person. Direct demand for food and indirect demand for feed crops depend specifically on the amount of livestock-related products in the diets. If less meat and other livestock products are consumed in a scenario, vegetal parts in human diets increase, but the amount of required feed crops decreases, and vice versa. The exogenously given projections for food demand in the model are derived from scenario information on kcal consumption per capita and population growth (Valin et al., 2014). Based on historical national time series on GDP and food and livestock demand, the amount of consumption per capita varies.

The SSP indicator “environment” is not relevant for our study, as there are no differences between the two scenarios. In the environmentally not very sensitive SSP4 and SSP5, protected areas increase until 2100 by 50% compared to 2010. The indicator “technology” manifests itself as soil nitrogen uptake efficiency and livestock efficiency (the amount of feed needed to produce a certain amount of livestock products). The indicator “globalization” is implemented in our modeling framework through different rates of trade liberalization (Table 2).

Table 2: Translation of SSP indicators into model parameters and their implementations for the poverty and the prosperity scenario.

Model parameters (SSP indicators)	Poverty scenario (based on SSP4)			Prosperity scenario (based on SSP5)		
	Sub-Saharan Africa	Middle East and North Africa	South Asia	Sub-Saharan Africa	Middle East and North Africa	South Asia
Population in million people in 2030	1396	511	2054	1240	508	2025
Kcal per capita in 2030 (based on GDP)	2531	3245	2621	2707	3394	2763
Demand for food crops in Peta Joule in 2030 (based on population/GDP)	4462	2460	7013	4191	2100	7088
Share of livestock products in the diet in 2030 (based on GDP)	0.09	0.15	0.14	0.10	0.15	0.14
Trade liberalization (Globalization)	Starting from 2010, trade barriers are relaxed by 10% per decade for developed regions, but are kept constant for developing regions.			Starting from 2010, trade barriers are relaxed by 10% per decade globally.		
Livestock intensification (Technology)	Slow			Fast		
Nutrient efficiency (Technology)	High			Medium		

The two extreme socioeconomic scenarios lead to different future developments. The preference for economic growth leads in the scenario of prosperity to a globalized world with open trade and an increase in the standard of living in all parts of the world, exemplified by high per capita livestock and calorie consumption. The scenario of poverty is represented through a world of increasing inequality where especially poor countries suffer under high population as well as low GDP growth, with the consequence of a low kcal per capita consumption. For developed countries the narrative is similar to the prosperity scenario with liberalized trade between them and high GDP growth. Table 2 shows how the qualitative SSP indicators are translated into model parameters.

The overall regional demand for food crops is partly very similar between the two scenarios (e.g. in South Asia). This is due to the fact that overall demand is a combination of per capita demand and population, since in the poverty scenario population is high while GDP-related per capita demand is low, and vice versa in the prosperity scenario: the effects offset each other. Livestock shares are partly based on GDP projections. While in Africa the impact of a better economic development in a prosperity scenario is already visible in 2030, the share of livestock consumption in South Asia and Middle East and North Africa is equal in both scenarios in 2030 due to a relatively high GDP in 2005 and a resulting lower increase. Differences between the scenarios regarding the livestock share in the two regions become more apparent towards the middle of the century.

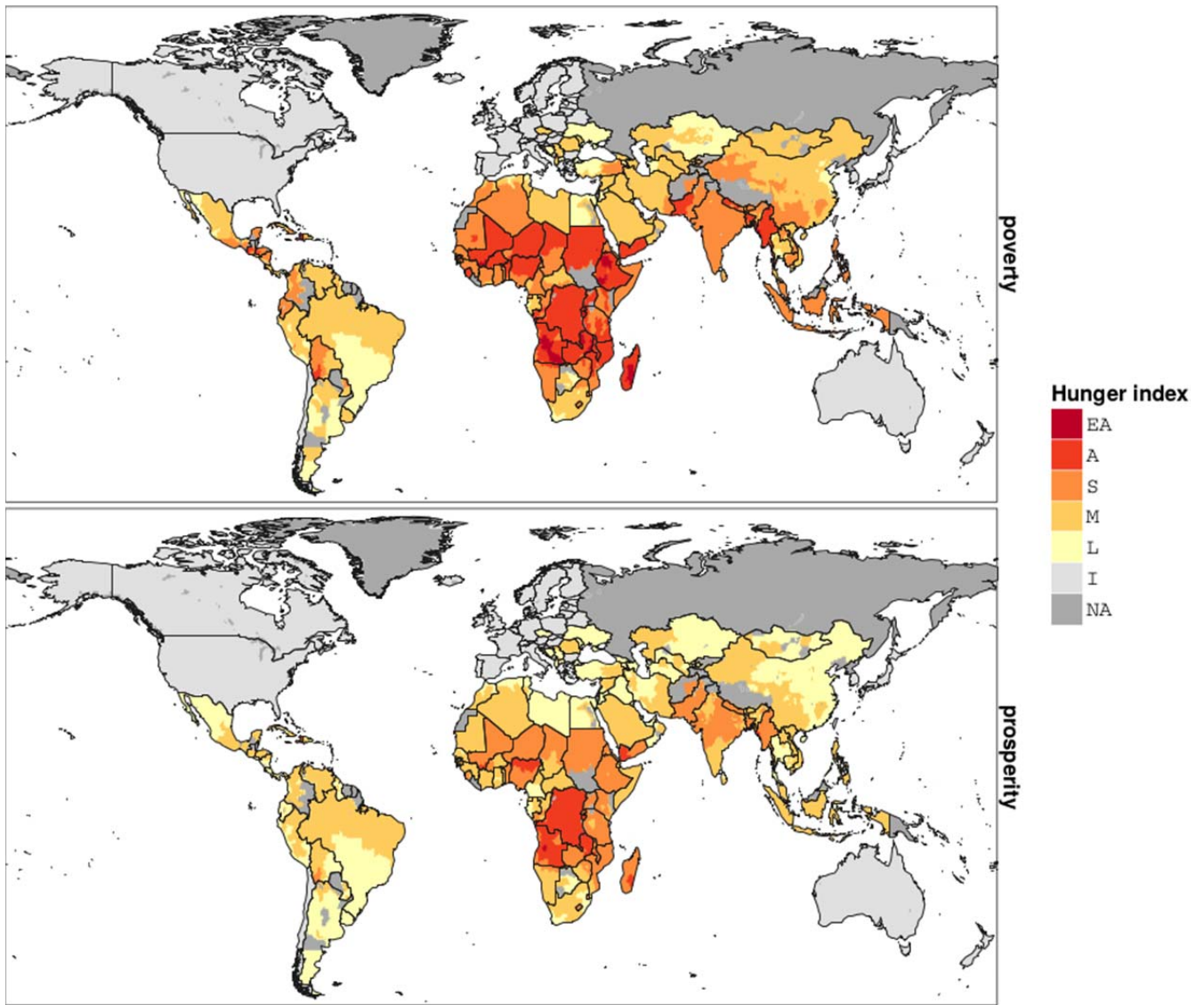


Figure 3: Spatially explicit Vulnerability to Hunger Index in 2030 for the poverty and prosperity scenario. Light grey indicates industrial countries (I), dark grey reflects that no data are available nor can they be deducted (NA). (Hunger levels: EA = extremely alarming, A = alarming, S = serious, M = moderate, L = low.)

In our study, not only the model implementation is scenario-specific, but also the projection of the Vulnerability to Hunger Index. The Vulnerability to Hunger Index is based on scenario-dependent economic poverty data explained in section 2.2.1. Figure 3 depicts Vulnerability to Hunger Index projections for the poverty and prosperity scenario for 2030. Countries where no data were available for the Vulnerability to Hunger Index, like South Sudan, are shown in dark grey on the map, countries which are industrialized and therefore in general not prone to hunger at a larger scale are shown in light grey.

2.3.2 Climate scenarios

In this study, the high-end Representative Concentration Pathway (RCP8.5) with a radiative forcing of 8.5W/m^2 in the year 2100 relative to pre-industrial values (resulting average temperature increase at the end of the century 3.7°C) and a scenario with no future climate change are compared (Moss et al., 2010). The RCP8.5 emission scenario has been implemented in 5 general circulation models and climate results have been provided by the CMIP5 project available at <http://cmip-pcmdi.llnl.gov/cmip5/> (Taylor et al., 2012). Climate scenarios were selected based on availability of

bias-corrected data sets from the ISI-MIP project for the following general circulation models: GFDL-ESM-2.0, Hadley-GEM 2, IPSL-CM5A-LR, MIROC-ESM-CHEM, Nor-ESM1-M. Results were supplied to LPJmL as monthly data fields of mean temperature, precipitation, cloudiness and number of wet days (Hempel et al., 2013). Yield and water availability values used in this study are the mean for the results of the 5 general circulation models. We use the mean of the 5 general circulation models as we do not know which of the models produces the most reliable result.

LPJmL simulations of crop yields and water availability used as input in the MAgPIE model are generated without CO₂ fertilization. The higher atmospheric carbon dioxide concentration, due to human induced increases in emissions, will possibly lead to enhanced crop growth. Leaving it out might therefore lead to overestimating the negative effect of climate change on crop yields. But the implementation of CO₂ fertilization is subject to a high level of uncertainty (Long, 2006; Tubiello et al., 2007). The beneficial effect of CO₂ fertilization on crop yields require an adjusted management to enable the production of higher quantities, otherwise nitrogen could become limiting (Bloom et al., 2010; Leakey et al., 2009; Parry and Hawkesford, 2010). Changes in the chemical composition of plants under higher atmospheric CO₂ concentrations could also have negative effects on yields, as they were shown to impede the plants' defense mechanisms against insect damage (Dermody et al., 2008; Zavala et al., 2008). Müller and Robertson (2014: 46) conclude therefore: "As both crop and economic models on a global scale are not capable of addressing this much detailed feedback, the assumption to ignore CO₂ fertilization effects is not unreasonable at this time".

In order to show the range of results from the different climate models and methodologies, Figure 4 shows differences in yields between climate change and no climate change for each general circulation model with and without CO₂ fertilization for all ten MAgPIE regions. These results show maximum potential yields from LPJmL and might differ from the yields used as MAgPIE input, since LPJmL yields are calibrated in MAgPIE in the first time step to take account of imperfect management. While spatially explicit projections of yields might be quite different between the 5 general circulation models, projections of average food crop yields with and without CO₂ fertilization differ by not more than 7% between the different general circulation models. While in 2030 the sign of the yield difference is the same in each of the 10 regions, in 2080 it differs for the simulation results with CO₂ fertilization for some regions, thus indicating that the uncertainty of the modeling results is clearly higher (Figure 18 in the Appendix).

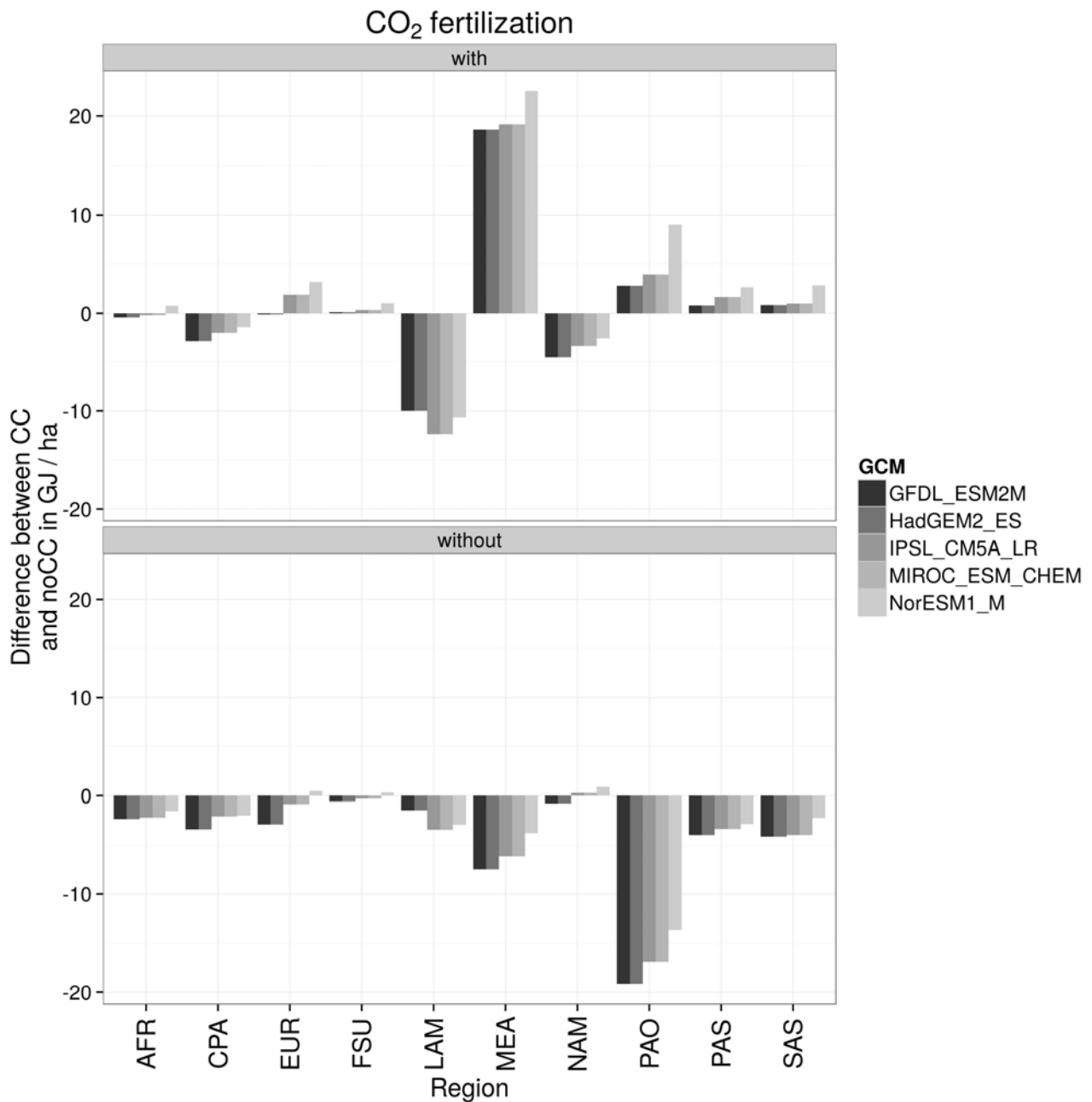


Figure 4: Regional average difference in biophysical yields of food crops for the 5 different general circulation models (GCM) with and without CO₂ fertilization for RCP8.5 compared to a no climate change scenario (climate change – no climate change) for the year 2030 and for the 10 MAgPIE regions. (Names of regions: AFR = Sub-Saharan Africa, CPA = Centrally Planned Asia, EUR = Europe, FSU = Former Soviet Union, LAM = Latin America, MEA = Middle East and North Africa, NAM = North America, PAO = Pacific OECD, PAS = Pacific Asia, SAS = South Asia.)

2.3.3 Market access scenarios

Market access is an important factor for poverty since it determines how easily rural farmers are able to sell their products. Accessibility of markets is represented in MAgPIE through intra-regional transport costs. High transport costs represent bad market access and low transport costs represent good market access for farmers. In the market access scenarios, the different transport costs at grid level are uniformly multiplied by a global parameter. This means that in poor and rich regions the change in transport costs is the same, but since rich regions can be assumed to already have low transport costs, poor regions are going to benefit over-proportionally.

Transport costs in MAGPIE are calculated based on the travel-time from an area of production to the next city with more than 50,000 inhabitants and on transport costs per tonne and minute for each commodity (Nelson, 2008). In the scenario with good market access, we implement the transport costs from the cell with the cheapest transport costs globally and therefore the cell with the best market access, everywhere. This is preferred to using no transport costs at all, since a no transport cost scenario can lead to an implausible land use pattern where land expansion does not follow the already existing infrastructure, but agricultural land appears randomly and remote from current production. For the bad market access scenario, we use transport costs which are twice as high as in the default case and therefore worse than in the current situation. In our implementation, transport costs remain constant over time.

2.3.4 Agricultural technological progress scenarios

In order to represent an optimistic and pessimistic technological progress scenario, we vary the yield elasticity with respect to investments into agricultural technical change. The currently implemented yield elasticity is 0.27 (Dietrich et al., 2014). For representing fast and slow technological progress, we choose two alternative scenarios in which we set the elasticity to 0.32 (cheap technical change corresponding to fast technological progress) and 0.22 (expensive technical change corresponding to slow technological progress). These values were taken from the paper by Schmitz et al. (2012), where the authors tested the range for possible yield elasticities based on empirical data. A high yield elasticity implies that investments are highly profitable and lead to a fast increase in yields and vice versa for a low yield elasticity. The yield elasticity is a global parameter, but resulting technological progress differs across world regions. For regions with currently low land-use intensity, yield-increasing technological change can be achieved at lower costs (Dietrich et al., 2014).

2.3.5 Reference scenarios

We show our results always relative to reference scenarios without climate change, but with the same socioeconomic setting, in order to estimate the impact of climate change – *ceteris paribus*. Market access and technical progress scenarios are based on the poverty scenario in order to see the effects of changing parameters for the scenario more prone to poverty (Table 3).

Table 3: Overview of scenario settings used in this study.

Climate scenarios	Socioeconomic scenarios	Market access	Technological progress
no climate change	poverty	medium	medium
RCP8.5	poverty	medium	medium
no climate change	prosperity	medium	medium
RCP8.5	prosperity	medium	medium
no climate change	poverty	good	medium
RCP8.5	poverty	good	medium
no climate change	poverty	bad	medium
RCP8.5	poverty	bad	medium
no climate change	poverty	medium	fast
RCP8.5	poverty	medium	fast
no climate change	poverty	medium	slow
RCP8.5	poverty	medium	slow

3 Results and discussion

In sections 3.1 and 3.2, we describe and discuss the results for the agricultural indicators and combine them in section 3.3 with the Vulnerability to Hunger Index, resulting in the Agricultural Vulnerability Indicator. Since hunger is relevant only in some parts of the world, we show results for the regions currently most affected: Sub-Saharan Africa, Middle East and North Africa and South Asia. We use the world regions as defined by the World Bank Group, but based on the almost identical MAgPIE regions. Sub-Saharan Africa (SSA) corresponds to the MAgPIE region Sub-Saharan Africa (AFR), but includes Western Sahara. Middle East and North Africa (MNA) correspond to the MAgPIE region Middle East/North Africa (MEA) excluding Western Sahara. South Asia (SAS) without Myanmar corresponds to the MAgPIE region South Asia (SAS).

The agricultural indicators discussed in the sections are crop yields, crop production, and Costs of Food. Changes in yields are generated with the biophysical model LPJmL and are therefore independent of socioeconomic assumptions, while production and Costs of Food are shown for the poverty and prosperity scenario.

3.1 The impact of climate change on biophysical indicators

In all three regions under consideration (Middle East and North Africa, South Asia, and Sub-Saharan Africa), the average yield of food crops decreases with climate change compared to no climate change. The biophysical projections show that by 2030 average yields of food crops will decrease in the Middle East and North Africa by more than 7%, in South Asia by more than 5%, and in Sub-Saharan Africa by more than 4% (Figure 8, left panel).

Not only at an average regional level but also locally yields predominantly decrease in the climate change³ scenario. The countries which are most affected are Sudan, Oman and parts of Saudi Arabia, Somalia, Ethiopia and Kenya. Significant yield decreases of more than 7% can also be found within the Sahel zone. Only in Botswana, Namibia and parts of South Africa and Ethiopia do average food crop yields increase (Figure 5, upper panel).

³ When analyzing yield results, one should keep in mind that these yields reflect current levels of management intensity and current geographical distribution of managed land. This means that cell-specific changes in yields do not necessarily correspond to cell-specific changes in levels of agricultural production.

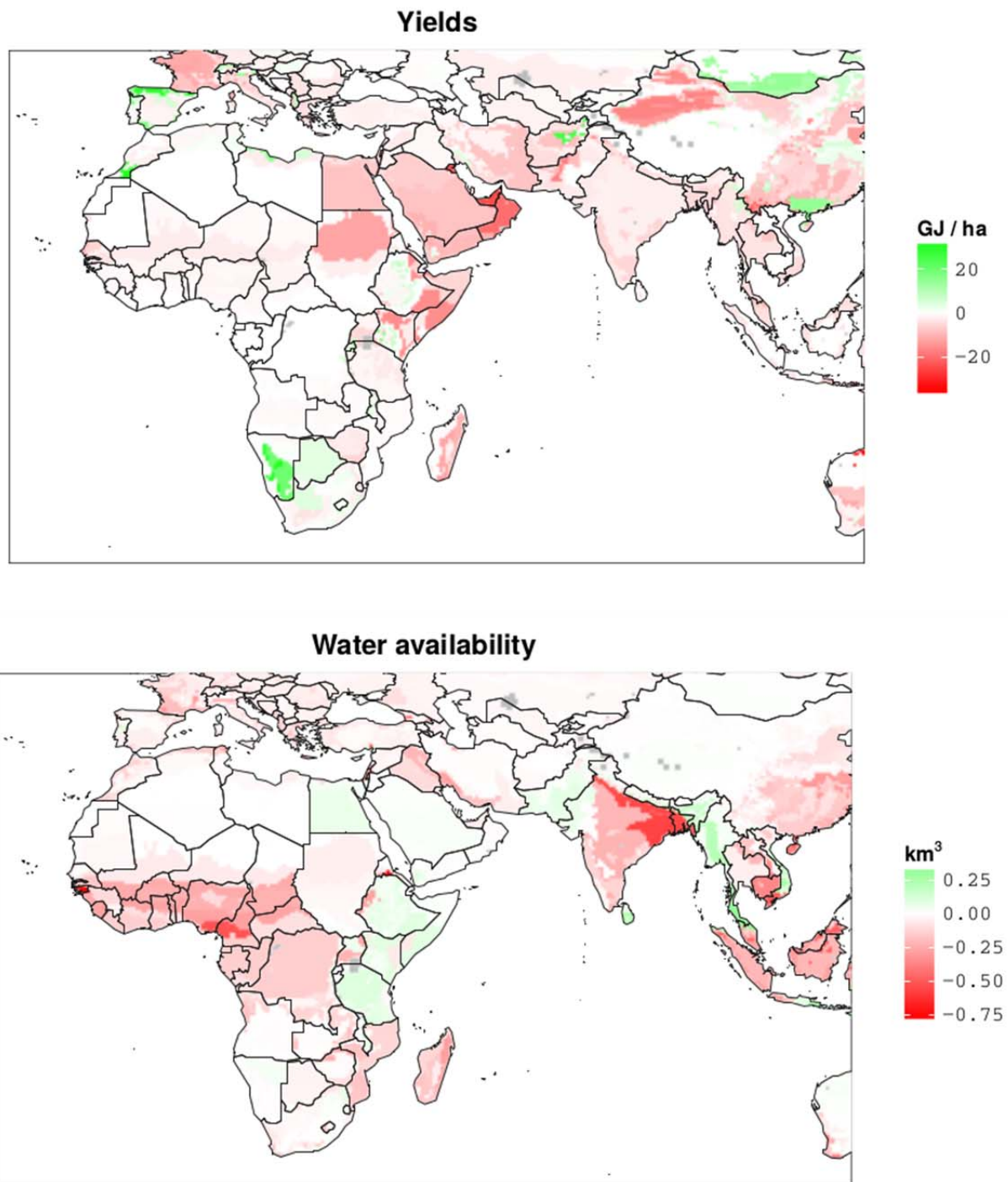


Figure 5: Cellular average difference in yields of food crops and biophysical water availability in 2030 for RCP8.5 compared to a no climate change scenario (climate change - no climate change). Positive values (green) indicate that yields/water availability increase with climate change, while negative values (red) show that yields/water availability decrease.

Biophysical water availability, which is a precondition for irrigated production, decreases most in the western and central part of tropical Africa, south of the Sahel, as well as in the north of India. In Egypt, Ethiopia, Kenya, Tanzania, Somalia, as well as in Pakistan, water availability is projected to increase with climate change. Regions which are already water scarce are not impacted (Figure 5, lower panel).

3.2 The impact of climate change on agroeconomic indicators

We use MAGPIE here as a tool to explore future agricultural production and Costs of Food under different climate and socioeconomic conditions. Due to the uncertainty in input data such as yields and water availability as well as model limitations (Section 4.3), quantitative results should be considered with care.

3.2.1 Climate-induced changes in agricultural production

In Sub-Saharan Africa, average regional production decreases with climate change in the poverty and prosperity scenario by 1% and 2%, respectively. Production decreases in the Sahel and south of it in both scenarios. The increase in yields in Namibia leads to an increase in production in both socioeconomic scenarios, but production increases also in Tanzania where yields go down. In Malawi, Zimbabwe and parts of the Democratic Republic of the Congo and Zambia as well as in Egypt, production increases in the poverty scenario, but decreases in the prosperity scenarios. In most parts of Central Africa (Congo), there is no change in production because large parts are covered with tropical forests. Although yields increase in Botswana, the lack of change in production is due to the lack of crop production with and without climate change.

Total production in South Asia decreases only by 1% in the poverty scenario, but by 5% in the prosperity scenario. Although yields decrease everywhere in South Asia, production increases in Pakistan and parts of India in both socioeconomic scenarios, but the production increase is stronger in the poverty scenario. Production decreases in the rest of India.

Overall production in Middle East and North Africa increase by 1% in the poverty scenario with climate change and by 6% in the prosperity scenario, but the producing countries differ. Agricultural production increases in Morocco in the poverty scenario and there is a mixed pattern of decreasing and increasing local production in the prosperity scenario. In Libya there is no significant decrease in yields and production increases in both scenarios. In Egypt yields decrease with climate change and production decreases in the prosperity scenario and increases in the poverty scenario. In Saudi Arabia yields decrease due to climate change, but production increases in the entire country in the prosperity scenario and in parts of the country in the poverty scenario (Figure 6 and Figure 8).

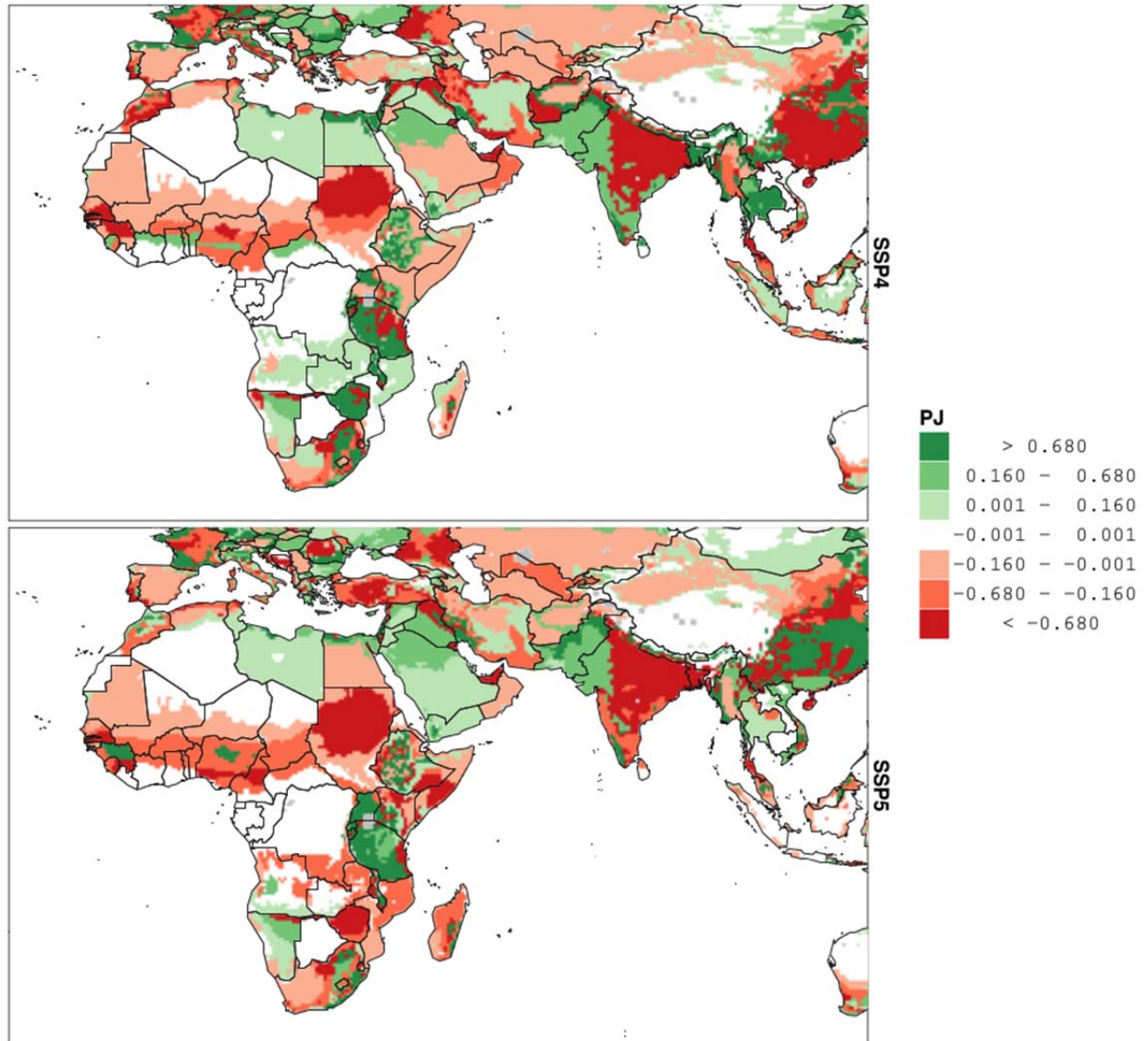


Figure 6: Cellular average difference in production of food crops for each 0.5° grid cell in 2030 for RCP8.5 compared to a no climate change scenario (CC-noCC) and two Shared Socioeconomic Pathways (SSP4, SSP5). Positive values (green) indicate that production increases with CC, while negative values (red) show that production decreases.

3.2.2 Adaptation strategies are different for the focus regions

Model-based reactions to climate-induced decreases in productivity are different for each of the three considered world regions as well as for the different socioeconomic scenarios. In the prosperity scenario, the regions Sub-Saharan Africa and South Asia may adapt by changing trade patterns (increasing imports and decreasing exports). Due to high trade barriers in the poverty scenario (Figure 23), expanding agricultural area is the prevailing strategy. In the poverty scenario, Sub-Saharan Africa and South Asia use 9% and 7% more agricultural land compared to the no climate change scenario, while in the prosperity scenario agricultural area increases only by 5% in South Asia and even decreases by 8% in Sub-Saharan Africa (Figure 22 in the Appendix). The seemingly contradiction between a decrease in production in the poverty scenario and an increase in production area is a result of the crop-specific trade barriers. Even if, as a result of climate change, crop yields are very low in this region, demand has to be fulfilled and production has to be adjusted. Adjusted

production of low yielding crops will therefore lead to an over-proportional expansion of agricultural area. Not only changes in crop yields but also the reduction of available irrigation water alters regional production patterns. In Sub-Saharan Africa, the decrease of available irrigation water leads to a decrease of irrigated production in the poverty and prosperity scenario by 25% and 29% respectively, while in South Asia irrigated production decreases by 3% for the poverty scenario and 5% for the prosperity scenario (Figure 21 in the Appendix). Both regions, but especially Sub-Saharan Africa, where climate change has a partially positive impact, react to climate change in the model by concentrating production in areas where yields are positively or marginally affected, thus relieving the pressure on areas where productivity has decreased.

In order to adapt to climate change, Middle East and North Africa cannot resort to expanding agricultural area, since the land potentially available for agriculture is already at its limit. Nor can it adapt by increasing imports, because trade constraints in the model are already binding even without climate change⁴. There are several crops⁵ for which the domestic self-sufficiency constraints are already binding in the scenario without climate change. Sustaining production of these crops despite decreasing yield levels in the model can only be achieved through massive investments in yield increasing technology. The decrease of yields therefore has to be completely compensated by improved management and technological progress. Required investments in technical change lead to a yield increase of 26% compared to the no climate change scenario in the poverty scenario and of 20% in the prosperity scenario. In our model implementation, technical change investments increase the yield of all crops proportionally. The crop group which triggers the massive investment in technical change is temperate cereals, which is impacted by strong yield decreases (9% compared to an average of 7%) while at the same time representing the most important crop in the region (share in overall production: 35% in the poverty scenario and 40% in the prosperity scenario), thus putting enormous pressure on agricultural systems.

The crop group profiting most from the spillover effect of technical change investments is tropical cereals. While biophysical yield is little affected by climate change (1%), the resulting yield after technical change is much higher in the scenario with climate change compared to the scenario without (namely 30% in the poverty scenario and 40% in the prosperity scenario)⁶. The resulting comparative advantage of a high regional tropical cereals yield leads to an increase of production utilized exclusively for export. Since self-sufficiency constraints in the prosperity scenario are only binding for temperate cereals, agricultural production is concentrated even more on tropical cereals, while in the poverty scenario resources have to be concentrated into domestic production.

Moreover, production shifts from irrigated (high yields) to rainfed (low yields) due to the decrease of water availability in the Middle East and North Africa. This is visible in the decrease of irrigated production of 9% in the poverty scenario and 6% in the prosperity scenario, as well as in the increase of rain-fed production of about 30% and 35% respectively in the poverty and prosperity scenario, compared to the no climate change scenario.

⁴ See Section 2.1.2 for an explanation of the model implementation of trade.

⁵ The crops with binding self-sufficiency constraints in Middle East and North Africa include: temperate cereals, rice, maize, groundnut, oil palm, sugar and cassava.

⁶ The higher relative yield increase in the prosperity scenario results from the fact that in the scenario without climate change less technical change investments were necessary resulting in a lower reference yield, the absolute average yield is for each of the two climate scenarios higher in the poverty scenario than in the prosperity scenario.

3.2.3 Climate-induced changes in Costs of Food

The change in Costs of Food is spatially very diverse and varies also between the different socioeconomic scenarios. In the poverty scenario, more countries suffer from climate-induced price increases than in the prosperity scenario (Figure 7). The average regional cost increases are highest in the Middle East and North Africa in the poverty scenario. Here, average Costs of Food increase by 35% under climate change compared to 17% in the prosperity scenario (Figure 8).

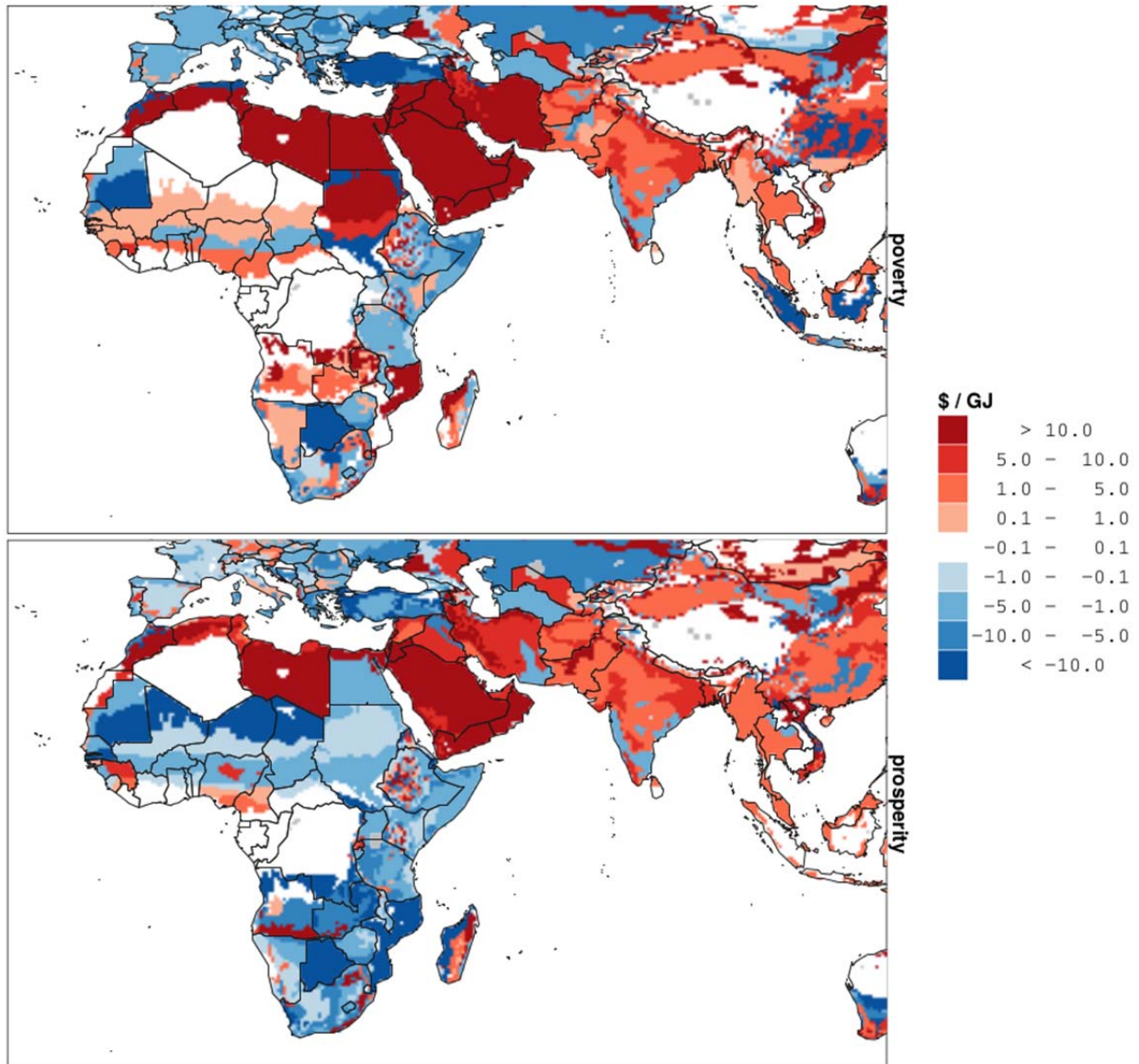


Figure 7: Cellular average difference in Costs of Food in 2030 for RCP8.5 and two socioeconomic scenarios compared to a no climate change scenario (climate change – no climate change). Positive values (red) indicate that Costs of Food increase, while negative values (blue) show that Costs of Food decrease.

Increases in Costs of Food of more than 10US\$/GJ in both socioeconomic scenarios affect Morocco, the very northern part of Algeria, Tunisia, Libya, Egypt, Saudi Arabia, Yemen and Oman. In Egypt, Costs of Food increase in the poverty scenario and decrease in the prosperity scenario. Average Costs of Food decrease in Sub-Saharan Africa in both scenarios, in the poverty scenario by 2% and in the prosperity scenario by 17%. From a national perspective, Costs of Food decrease under climate change in Mauritania, Botswana, Somalia, Tanzania and Zimbabwe in both socioeconomic scenarios, but increase

in the poverty scenario and decrease in the prosperity scenario in Sudan, partly in the countries south of the Sahel, Angola, Zambia, the south of the Democratic Republic of Congo and Mozambique. In South Asia, average Costs of Food increase in both socioeconomic scenarios, by 12% in the poverty scenario and 18% in the prosperity scenario. Costs of Food increase in most of India as well as in Afghanistan and patterns are quite similar between the poverty and prosperity scenario (Figure 7).

3.2.4 Climate change does not necessarily lead to increasing Costs of Food

Our model results show that Costs of Food decrease under climate change in Sub-Saharan Africa on average by 2% in the poverty scenario and by 17% in the prosperity scenario. The decrease of Costs of Food in many countries in Sub-Saharan Africa originates on the one hand from a change in trade flows in the model, which leads to a decrease in overall production, and thus to a concentration of production in the most profitable areas. On the other hand, Costs of Food decrease in the model because climate change has a partially positive impact on yields. If production is shifted to these crops (cassava, maize, sugar cane and sunflower) as well as more favorable areas, Costs of Food decreases. The increase of Costs of Food in some countries as well as the lower average decrease of Costs of Food in the poverty scenario compared to the prosperity scenario results from less imports, which leads to larger agricultural areas being cultivated with low yielding crops and less possibility to grow the most profitable crops.

Due to higher population growth and more trade barriers, average absolute Costs of Food in South Asia are already without climate change higher in the poverty scenario than in the prosperity scenario (24US\$/GJ in the poverty scenario, 21US\$/GJ in the prosperity scenario), resulting in a higher relative impact of climate change on the prosperity scenario (Figure 8).

While production of food crops decreases under climate change in the model by 1% in the poverty scenario and 5% in the prosperity scenario due to an increase in imports and decrease of exports, Costs of Food increase by as much as 12% in the poverty scenario compared to 17% in the prosperity scenario. The high increase in Costs of Food under climate change in the prosperity scenario despite decreasing production can be explained by the high demand for livestock products in the prosperity scenario in developed regions such as North America, Europe, Australia and Japan. While exports of food crops decrease in South Asia in the prosperity scenario, feed crop production of mainly sugar and soybean, necessary for the export production of ruminant products, increase by 8% and 23% respectively, compensating the decreasing crop yields in other world-regions. In comparison, in the poverty scenario exports of ruminant products are lower under climate change, since the negative impact of climate change cannot be compensated by trade, and food crop production replaces feed production. Despite investments in cost-increasing technical change, climate-induced yield decreases are not completely compensated. Compared to the respective scenario without climate change (where yields are also enhanced by technical change), they are 7.5% (poverty scenario) and 9.5% (prosperity scenario) lower. The lower yields lead in both scenarios to higher factor costs per tonne, resulting in higher Costs of Food.

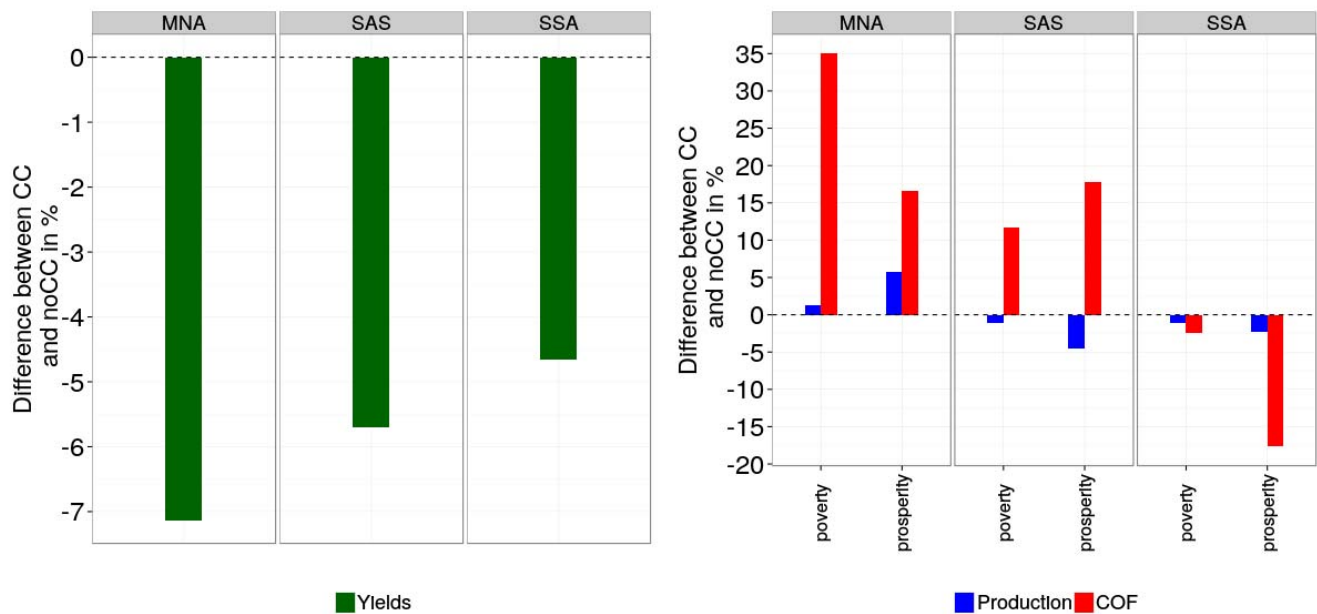


Figure 8: Regional average difference in biophysical yields of food crops (left panel), production of food crops and Costs of Food (COF) (right panel) for RCP8.5 compared to a no climate change scenario (climate change - no climate change) for two socioeconomic scenarios in 2030. (Region names: MNA = Middle East and North Africa, SAS = South Asia, SSA = Sub-Saharan Africa.)

According to our simulations, Middle East and North Africa compensates the climate-induced decrease in yields by investing in yield-increasing technical change. Yield increase resulting from technical change investments is higher in the poverty scenario than in the prosperity scenario, due to the high self-sufficiency constraints of almost 100% and a high overall food demand due to a larger population. In the poverty scenario the increase in Costs of Food is even higher since technical change becomes more expensive when the yield level is already high, meaning that the additional necessary yield increase in the poverty scenario is over-proportionally expensive. This leads to overall technical change investments which are 103% higher in the poverty scenario and 84% higher in the prosperity scenario compared to the no climate change scenario (Figure 24 in the Appendix). The decrease of production in Egypt and the resulting decrease in Costs of Food in the prosperity scenario is due to the fact that trade is less restricted in the prosperity scenario, and production can therefore be shifted to more productive areas.

3.3 Assessing agricultural vulnerability under climate change

In order to better understand the impacts of climate change on poverty, we combine the agricultural indicator Costs of Food with the Vulnerability to Hunger Index projections for the two socioeconomic scenarios (Figure 3). We use the hunger level categories defined by IFPRI (Table 1) and impact categories for Costs of Food as defined in Table 4 in the following table and maps. Since 1GJ corresponds to 239,000 kcal, a climate-induced increase of Costs of Food of 0.1US\$/GJ (defined as the lowest threshold for being impacted) correlates to an increase of 0.001US\$ per 2390 kcal. Since according to Smil (2001), 2200 kcal per day satisfy the metabolic energy requirements of an average person, while an additional 400 kcal are needed and defined as unavoidable waste, the 2390 kcal can be interpreted as the required number of calories per day for a person to stay healthy. Therefore, we can approximately say that people will pay additional 0.001 US\$ or more per day for their food when impacted by climate change in 2030 and included in the lowest impact category. Although this seems very low, it might be a non-negligible amount of money for a person living on less than 1.25 US\$ per day.

Table 4: Defining the categories for changes in Costs of Food due to climate change in 2030 used in the Agricultural Vulnerability Indicator. The two right-hand columns show the same values, but converted into different units.

Impact category	Description	Changes in Costs of Food in US\$/GJ due to climate change	Changes in Costs of Food in US\$ per day (US\$/2390kcal) due to climate change
EI	Extremely high impact	>10	>0.1
HI	High impact	5-10	0.05-0.1
SI	Strong impact	0.1-5	0.001-0.05
NNI	No negative impact	<0.1	<0.001

Figure 9 combines projections for the Vulnerability to Hunger Index (Figure 3) and the projections for the impact of climate change on Costs of Food for the two socioeconomic scenarios (Figure 7). The projections for the Vulnerability to Hunger Index, which are correlated to the economic development of the single countries, are quite different between the two socioeconomic scenarios. Although Vulnerability to Hunger decreases in 2030 in both scenarios compared to the year 2005 due to a general positive economic development, it decreases clearly more in the open and rich prosperity scenario.

Sub-Saharan Africa is most affected by hunger in the poverty scenario in 2030, where Vulnerability to Hunger is “extremely alarming” in parts of Ethiopia, Angola and Madagascar and “alarming” in most of the rest of the region. The situation is better in the prosperity scenario, but Angola and the Democratic Republic of Congo still suffer under an “alarming” Vulnerability to Hunger, while the rest of the region is characterized by either “serious” or “moderate” vulnerability. The overall vulnerability level is lower in Middle East and North Africa in 2030 than in 2005 in both socioeconomic scenarios. In India (South Asia), Vulnerability to Hunger is “serious” in the poverty scenario, but decreases in parts of the country to a moderate level in the prosperity scenario.

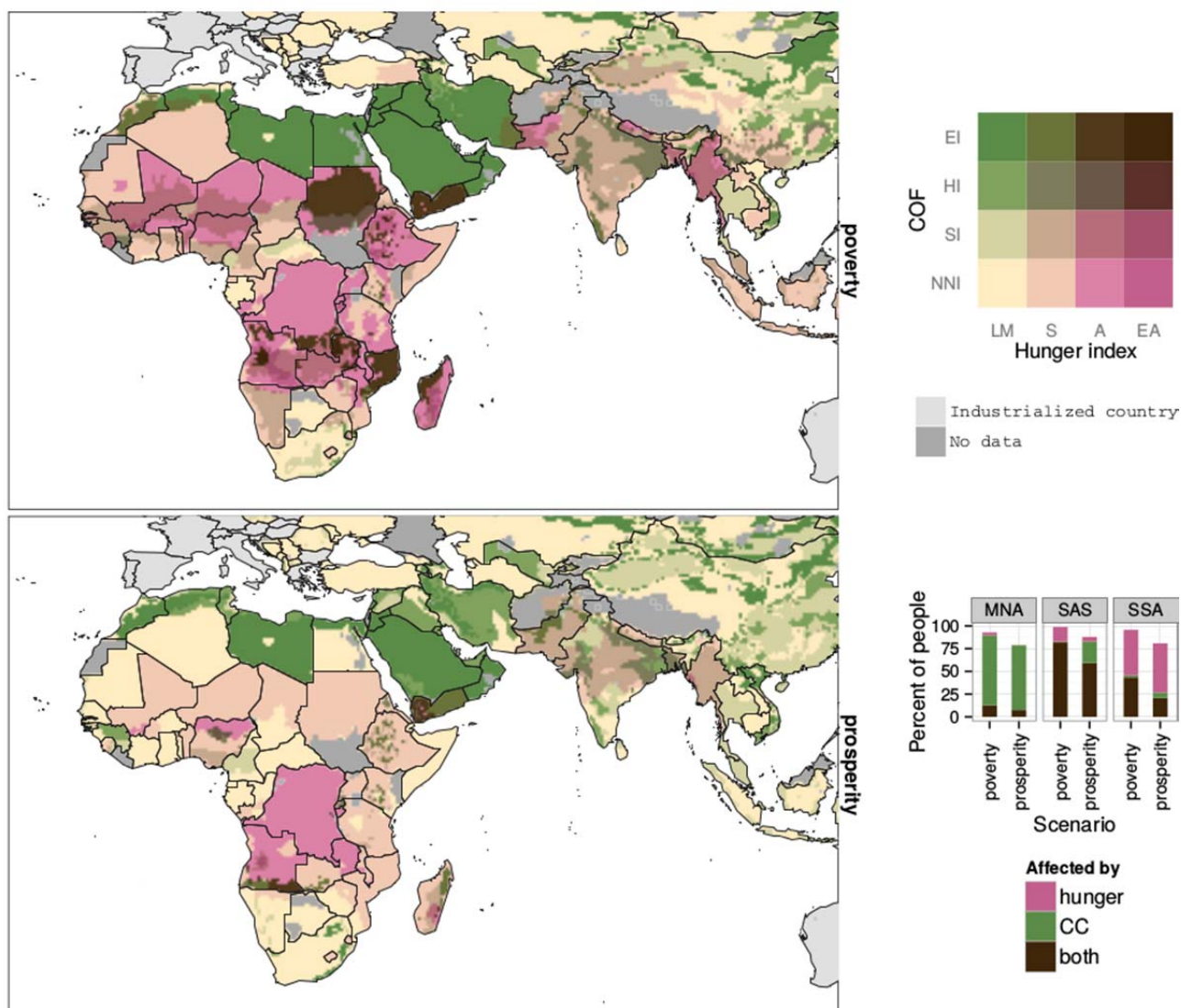


Figure 9: Agricultural Vulnerability Indicator, based on the differences in Costs of Food (COF) between RCP8.5 and a no climate change scenario and combined with the projected Vulnerability to Hunger Index for the year 2030 for the two socioeconomic scenarios (map). Percentage share of regional population affected by climate-induced increases in Costs of Food, exposure to hunger, and both (barplot).

(Hunger levels: EA = extremely alarming, A = alarming, S = serious, LM = moderate and low, Climate change impact categories: EI = extremely high impact, HI = high impact, SI = strong impact, NNI = no negative impact; Region names: MNA = Middle East and North Africa, SAS = South Asia, SSA = Sub-Saharan Africa.)

3.3.1 Regional and national results: Agricultural Vulnerability Indicator

While Middle East and North Africa suffers, according to modelling results, most under the consequences of climate change in 2030 by experiencing extremely high Costs of Food, a positive economic development leads to an improved situation concerning hunger. People are even less negatively impacted in the prosperity scenario, due to a lower increase of Costs of Food. Some parts of the region suffer in the poverty scenario under a high increase in climate-induced Costs of Food, such as Morocco and Northern Algeria, while their Vulnerability to Hunger is only low or moderate. In Libya and Egypt, a serious impact on Costs of Food is combined with a low and moderate vulnerability level. The situation improves for many countries in Middle East and North Africa in the prosperity scenario

compared to the poverty scenario, such as Libya and Algeria where the negative impact on Costs of Food is alleviated.

In Sub-Saharan Africa, climate change has a partly positive impact on agriculture, and due to increased trade production can be concentrated in the most productive areas, leading to even lower average Costs of Food. But as the economic situation, according to the projections, will improve only slowly, many people will still suffer from hunger. Since both, the Vulnerability to Hunger Index, as well as the climate-induced change in Costs of Food are more favorable in the prosperity scenario than in the poverty scenario, the overall situation regarding hunger is improved in the prosperity scenario. The most severe consequences of climate change in Sub-Saharan Africa can be observed for the poverty scenario in Sudan, Mozambique, parts of Zambia, Democratic Republic of Congo, Angola and Madagascar, where people with extremely alarming Vulnerability to Hunger are extremely impacted by the climate-induced changes in Costs of Food. The increase in Costs of Food is serious in the countries around the Sahel where Vulnerability to Hunger is alarming. No impact of climate change on Costs of Food as well as low Vulnerability to Hunger can be seen in South Africa. In the prosperity scenario, the countries in Sub-Saharan Africa are mostly better off than in the poverty scenario, partly due to the observation that climate-induced impacts on Costs of Food disappear in almost the entire region, except in small parts of Zambia, Angola, Kenya and Ethiopia, but also due to the lower overall Vulnerability to Hunger, which only remains alarming in Angola and the Democratic Republic of Congo.

In South Asia, Costs of Food will increase by 2030, but the negative effects cannot in all parts be alleviated by a positive economic development. Parts of the region will suffer from serious Vulnerability to Hunger as well as high impacts on Costs of Food. In this region, differences between the poverty and prosperity scenario are smallest. Vulnerability to Hunger in India and Pakistan becomes lower in the prosperity scenario compared to the poverty scenario, but the impact on Costs of Food, which is partially strong and high, remains almost everywhere unchanged.

3.3.2 Regional and national results: Number of people affected

Table 5 shows the number of people affected by climate-induced changes in Costs of Food. Here, spatially explicit population projections for the poverty and prosperity scenario (Section 2.2.2) are combined with the results from the Agricultural Vulnerability Indicator. The table shows the number of people who fall in one of the three most negative categories for impacts of climate change on Costs of Food and hunger level and omits people which are either not negatively impacted by climate change or fall into the lowest hunger level category. In the three regions combined, 2320M people seriously vulnerable to hunger are also strongly affected by climate-induced increases of Costs of Food in the poverty scenario. By contrast, in the prosperity scenario this number is reduced to 1448M people for several reasons. There are less people in total, average incomes are higher, a smaller share of the population is vulnerable to hunger, and negative climate impacts can be better compensated by trade.

Table 5: Number of people (in million) affected by climate-induced increases in Costs of Food (difference between RCP 8.5 and a no climate change scenario) sorted by different impact categories (rows) and Exposure to hunger for different Vulnerability to Hunger Index categories (columns) in 2030, regionally for a poverty and a prosperity scenario.

	Poverty				Prosperity			
Vulnerability to Hunger	Serious	Alarming	Extremely alarming	Sum	Serious	Alarming	Extremely alarming	Sum
Climate-induced changes in Costs of Food								
Sub-Saharan Africa								
Strong impact	205	224	28	457	164	8	3	175
High impact	9	14	0	23	26	16	0	42
Extremely high impact	13	81	16	110	33	2	0	35
Sum	227	319	44	590	223	26	3	252
Middle East and North Africa								
Strong impact	0	0	0	0	0	0	0	0
High impact	0	0	0	0	1	10	0	11
Extremely high impact	21	42	0	63	4	22	0	26
Sum	21	42	0	63	5	32	0	37
South Asia								
Strong impact	767	228	3	998	610	3	0	613
High impact	573	1	0	574	504	0	0	504
Extremely high impact	94	1	0	95	42	0	0	42
Sum	1434	230	3	1667	1156	3	0	1159

In Middle East and North Africa in the poverty scenario, 63M people or 12% of the regional population are exposed to at least serious hunger and are extremely high impacted by increases in Costs of Food. In the prosperity scenario, life improves for people by being less impacted by climate change, where 26M people are extremely high impacted and 11M people are highly impacted, as well as for people vulnerable to hunger, since 49M people less are vulnerable to at least serious hunger in the prosperity scenario compared to the poverty scenario. Consequently, the impact of climate change on people at risk of suffering under at least serious hunger is reduced to 37M people or 8% of the population in the prosperity scenario. This is in contrast to the high number of 443M people impacted by increases in Costs of Food in the poverty scenario and 371M in the prosperity scenario. The relatively small concurrence of people vulnerable to hunger and being impacted by climate change is due to positive economic projections for this region.

A large share of the population will be at risk of suffering at least serious hunger in Sub-Saharan Africa: 90% of the population (1267M people) in the poverty scenario and, due to positive economic development, 60% (903M people) in the prosperity scenario. Only a part of these people will also be affected by negative climate change, namely 590M people in the poverty scenario and 252M people in the prosperity scenario. This is due to the relatively good ability of the region to adapt to climate change, mainly by shifting production to marginally or positively affected areas. Unfortunately, this will only work for the short-time horizon until 2030. In the long run (until 2080), most of the positively affected areas in 2030 will also suffer from decreasing yields (Figure 31 in the Appendix).

In the poverty scenario in South Asia, 81% of the population live in regions where Costs of Food are at least strongly impacted by climate change and Vulnerability to Hunger is serious or worse (1667M people). This number of people is reduced to 1159M people or 59% of the population in the prosperity scenario, meaning that life improves for 508M people through better economic development and liberalized trade. The decisive improvement is related to a reduction of people exposed to hunger from 1990M in the poverty scenario to 1225M people in the prosperity scenario, while people affected by at least strong increases in Costs of Food are only reduced from 1627M people in the poverty scenario to 1623M in the prosperity scenario. In fact, most people in the poverty scenario are in the lowest impact category, leaving a smaller number of people highly impacted, while in the prosperity scenario 23% more people are highly impacted than in the poverty scenario. In the globalized prosperity scenario, South Asia produces livestock and feed crops for export into developed regions thus putting pressure on domestic Costs of Food.

If we confine our focus and look only at the two most extreme categories for the Agricultural Vulnerability Index we can identify the people whose daily Costs of Food increase by more than 0.05US\$ and which suffer under an at least alarming Vulnerability to Hunger. For Middle East and North Africa these are 8% of the population in the poverty scenario and 7% in the prosperity scenario. In Sub-Saharan Africa the difference between socioeconomic scenarios is remarkable, with 8% of the population belonging into the two extreme categories in the poverty scenario and 1.5% in the prosperity scenario. In South Asia only 0.1% of the population is concerned in the poverty scenario.

3.4 Adaptation options: Technological progress and improved market access

Negative climate impacts on agriculture and Costs of Food may be counterbalanced by potential adaptation measures. We investigate here two different options, namely investments into agricultural R&D, resulting e.g. in better adapted crop varieties or improved management systems, and improved market access facilitated by establishing infrastructure, enabling farmers to better reach markets. We show here only results the poverty scenario, in order to test the adaptation potential of the proposed measures. These adaptation options are different from the ones discussed in section 3.2.2 insofar as they are not model-inherent mechanisms necessary to generate sufficient food production. They rather serve as a sensitivity analysis for how a specific measure could buffer climate change impacts. While technological progress as an adaptation option is already implemented in the model, the effectiveness of infrastructure improvement is analyzed here for the first time.

3.4.1 Results: Technological progress

In the slow technological progress scenario, food crop production decreases in the three regions under consideration and Costs of Food increase with climate change in all cases. In Sub-Saharan Africa, the relative increase in Costs of Food in the slow technological progress scenario is highest with 250% (40US\$/GJ) compared to the no climate change scenario, Middle East and North Africa suffers most in absolute terms with Costs of Food increasing by 70US\$/GJ (80% in relative terms). The fast technological progress scenario, on the other hand, increases the ability to adapt to climate change. In Middle East and North Africa Costs of Food increase only by 12% compared to 37% in the default case. In Sub-Saharan Africa, Costs of Food even decreases in the fast technological progress scenario (Figure 10).

Poverty scenario - Technological progress

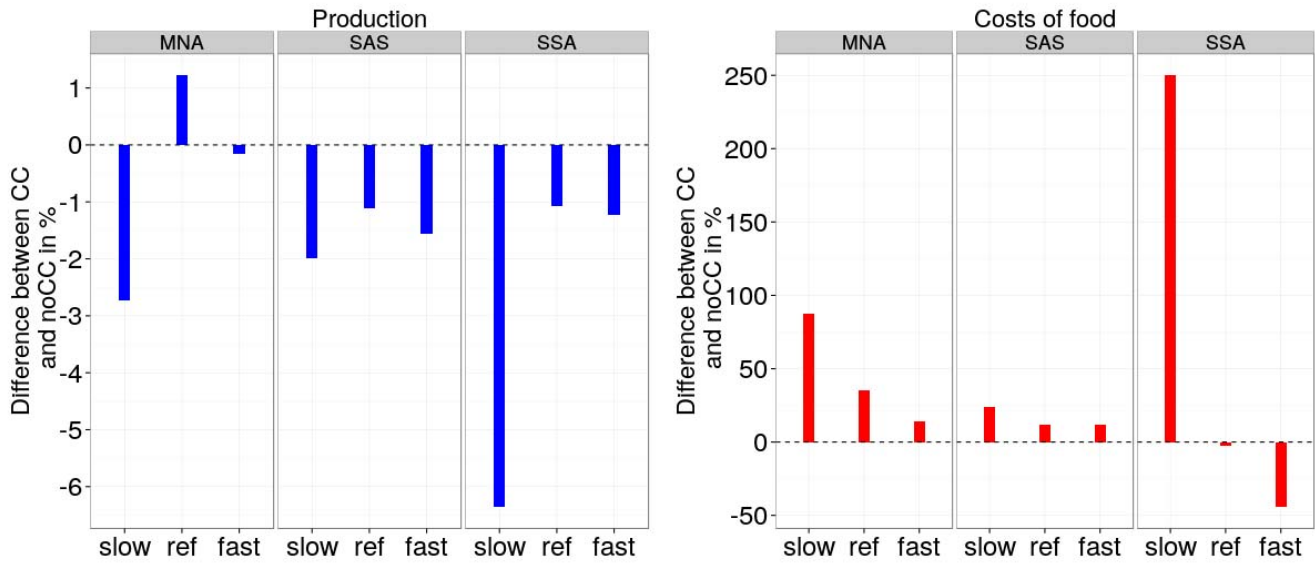


Figure 10: Regional percentage changes in food crop production and Costs of Food for RCP8.5 compared to a no climate change scenario (climate change - no climate change) for the year 2030, the poverty scenario and two technological progress scenarios. Reference (ref) refers to the poverty scenario with medium technological progress settings. (Region names: MNA = Middle East and North Africa, SAS = South Asia, SSA = Sub-Saharan Africa.)

3.4.2 Fast technical progress can alleviate negative climate change impacts

The decrease of production with climate change in almost all scenarios results from yield decreases which are compensated by increases in imports and decreases in exports⁷. The enhanced difficulty of adapting to climate change when R&D is expensive is reflected by the stronger decrease of production in the slow technological progress scenario compared to the reference and fast technological progress scenario in all regions. While slow technological progress is very problematic for our focus regions, fast technological progress does have little impact on production (Sub Saharan Africa and South Asia) or even reduces production compared to the reference case (Middle East Asia and North Africa). In these scenarios it is cost minimizing in the model to rather increase production in regions where additional yield increase is relatively cheaper and more efficient.

Although decreasing production in the slow technical progress scenario lowers overall production costs, Costs of Food increase since climate-induced lower yields have to be compensated by costly land expansion, higher factor input per ton, and necessary investments in expensive technical change. The high increase in Costs of Food in the slow technological progress scenario with high technical change costs in Middle East and North Africa can be easily understood when reconsidering that Middle East and North Africa is the region where in the model neither agricultural expansion, nor changes in trade are an adaptation option and that the region is therefore relying mostly on yield-increasing technical change to sustain production. While overall production costs increase with climate change in both scenarios in Middle East and North Africa as well as South Asia, resulting in increasing Costs of Food, they decrease in Sub-Saharan Africa (Figure 24 in the Appendix). The decrease in production and the resulting decrease of overall production costs of 1.8% in Sub-Saharan Africa are sufficient to lead to a decrease of Costs of Food in the fast technical progress scenario. Although in the slow technological progress scenario, overall costs decrease by 2.6% and production by 6.4%, Costs of Food increase with

⁷ An extensive discussion on the increase of production in the reference scenario in Middle East and North Africa can be found in section 3.2.2.

climate change. This can be attributed to the low investment in expensive technical change, leading to a low yield relative to the fast technological progress scenario. In order to compensate yield decreases due to climate change and fulfill food demand, agricultural area has to be expanded by 4Mha, which increases production costs and consequentially Costs of Food. The decrease in production is compensated by imports (Figure 23 in the Appendix). Maps with cellular explicit changes in production as well as Costs of Food can be found in the Appendix (Figure 25 and Figure 26 in the Appendix).

3.4.3 Results: Market access

Changes in market access for farmers through manipulating transportation costs impact the way economic regions react to climate change. Production decreases or stays constant under climate change in the bad market access scenario and increases or only slightly decreases in the good market access scenario. In Middle East and North Africa, and South Asia, Costs of Food increase with climate change in all scenarios, but increase more in the good market access scenario than in the bad. In Sub-Saharan Africa, Costs of Food decrease with climate change in the good market access scenario and increase in the bad market access scenario.

3.4.4 Better market access helps producers but might hurt local consumers

Transportation costs decrease in the good market access scenario and thus can make food production profitable even when the next market is relatively far away. Developing countries profit over-proportionally from low transport costs due to a badly functioning infrastructure in the reference case. Hence, the resulting comparative advantage as well as the negative impact of climate change on global crop yields provides the incentive to invest in R&D to boost yields. This effect leads for Middle East and North Africa and for South Asia to an increase in Costs of Food, since in order to increase production, overall technical change investments as well as overall costs for factor requirements, land conversion and transport have to increase. While producers will profit from better market access, the situation for consumers may worsen. In Middle East and North Africa, agricultural area actually decreases in the good market access scenarios although production increases. This is because some areas cannot be used at all for agricultural production under climate change, so area has to decrease, but it decreases less compared to the bad market access scenario, since some new and more productive regions can now be utilized.

In Sub-Saharan Africa, production and Costs of Food already decrease in the default case under climate change, as explained above, but with lower transport costs production becomes more profitable, meaning that production decreases by less than 0.5% compared to 1% in the default case. The strong decrease in Costs of Food can be explained by the fact that Sub-Saharan Africa is a region with high transport costs in the reference case. Improving market access therefore provides the opportunity to shift production profitably to more productive areas. Figure 28 in the Appendix shows that production shifts from Botswana and Angola to Namibia, which is one of the countries profiting most from climate change in 2030 in terms of yield increases (Figure 5).

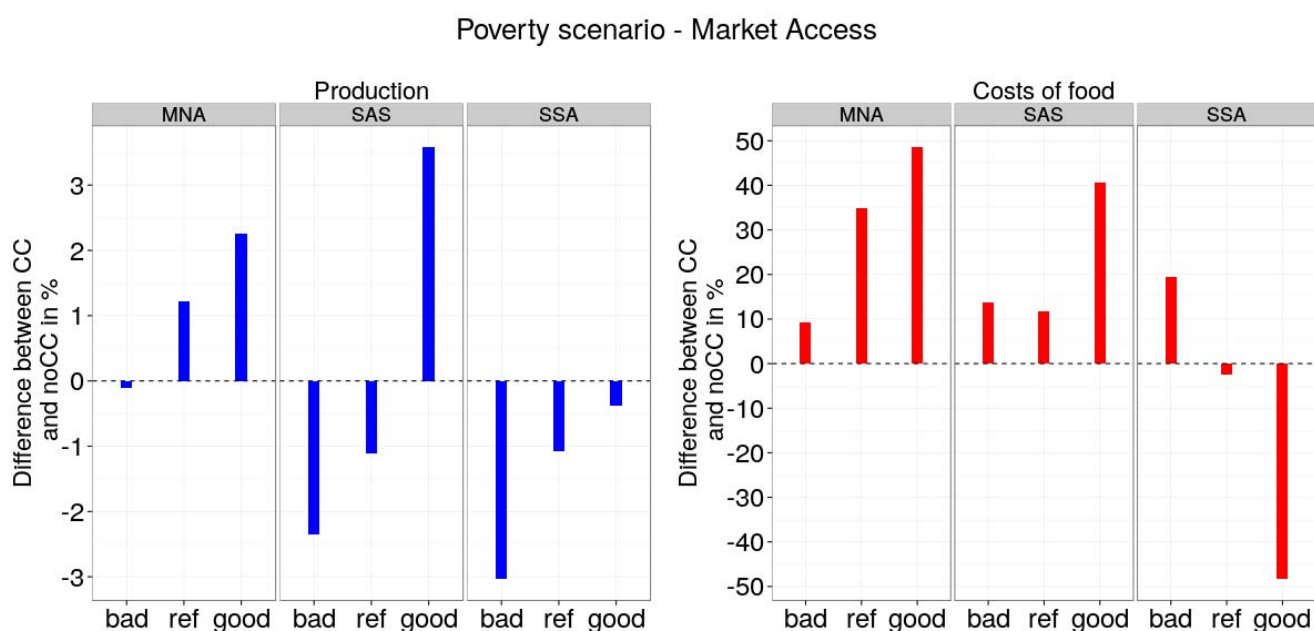


Figure 11: Regional percentage changes in food crop production and Costs of Food for RCP8.5 compared to a no climate change scenario (climate change - no climate change) for the year 2030, for the poverty scenario and two market access scenarios. Reference (ref) refers to the poverty scenario with medium market access. (Region names: MNA = Middle East and North Africa, SAS = South Asia, SSA = Sub-Saharan Africa.)

While developing regions profit over-proportionally from the good market access scenario, they are also over-proportionally negatively impacted by the bad market access scenario. In the model, Middle East and North Africa does not have the possibility to decrease production under climate change due to the lack of any other adaptation option. Therefore, it invests in technical change to increase yields, thus leading to increases in Costs of Food. South Asia and Sub-Saharan Africa have the possibility to adapt to climate change by increasing imports and decreasing exports, but since trade is not sufficient to compensate yield decreases, production partly has to be sustained through either investing in technical change or by expanding agricultural area, thus increasing Costs of Food. Maps with cellular explicit changes in production as well as Costs of Food can be found in the Appendix (Figure 28 and Figure 29).

3.5 The global perspective

Although - from a poverty perspective - the three decisive regions have been covered, due to tight linkages between world regions⁸, the effects of climate change on yields and Costs of Food in other regions as well as the effects of changes in trade are decisive.

3.5.1 Global impact of climate change on Costs of Food

While all regions, except for North America, are negatively impacted by climate change through decreases of average crop yields, the level differs. In Pacific OECD and Pacific Asia, average yields decrease by more than 8%, while in Europe, the Former Soviet Union and Latin America decreases are less than 3%. In terms of Costs of Food, the impact is very diverse between regions and socioeconomic scenarios. The Former Soviet Union and Latin America are relatively little impacted; in Europe, North America, Pacific OECD and Pacific Asia in the poverty scenario, Costs of Food even decrease under

⁸ The seven global regions beside the focus regions are now labelled with MAGPIE region names, since World Bank regions on a global scale are not comparable. A definition of the MAGPIE regions can be found in Figure 1.

climate change. Centrally-planned Asia is even worse impacted by increases in Costs of Food in the poverty scenario than Middle East Asia, namely by 43% (Figure 12).

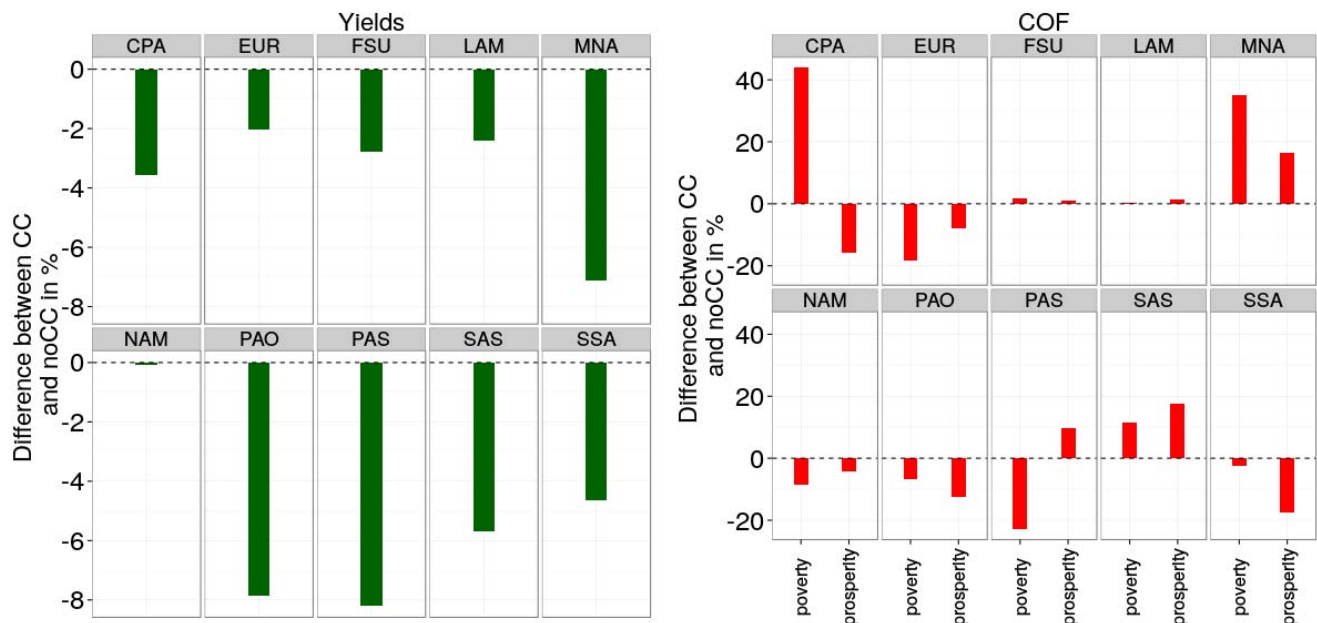


Figure 12: Regional average difference in biophysical yields of food crops (left panel), and Costs of Food(COF) (right panel) for RCP8.5 compared to a no climate change scenario (climate change - no climate change), right panel in 2030, for 10 world regions and two socioeconomic scenarios. (Region names: CPA = Centrally Planned Asia, EUR = Europe, FSU = Former Soviet Union, LAM = Latin America, MNA = Middle East and North Africa, NAM = North America, PAO = Pacific OECD, PAS = Pacific Asia, SAS = South Asia, SSA = Sub-Saharan Africa.)

The Former Soviet Union and Latin America are relatively little impacted by climate change. Although yields slightly decrease by about 2%, there is hardly any impact on Costs of Food in both socioeconomic scenarios, since both regions have spatially scattered patterns of yield changes, which means that production can be shifted to more productive areas (Figure 33 in the Appendix), but productivity levels are not high enough to buffer negative impacts of climate change in other regions through increases in exports. For North America, where average yields are not impacted by climate change, the positive impact of partial yield increases is even stronger. Costs of Food decrease in both socioeconomic scenarios because production is concentrated in productive areas, but decrease less in the prosperity scenario since North America uses its comparative advantage for export production to negatively affected regions. Exports of food crops increase under climate change by 39%. The major part of these exports comes from irrigated production, since improved water availability (Figure 34 in the Appendix) and increased demand create an incentive to invest in irrigation infrastructure. Europe is a region which is, despite decreasing average yields, positively impacted by climate change in many areas. In countries such as Poland, Slovakia, or Romania crop yields do not change, and in some countries such as Finland, northern Spain or England, yields increase (Figure 33 in Appendix). These areas are also mostly congruent with the areas where production increases (Figure 35 in the Appendix). Additionally, irrigated production increases through investments in irrigation infrastructure, thus increasing average yields. Finally, this leads to a decrease of Costs of Food, notwithstanding the fact that overall costs as well as exports increase in both socioeconomic scenarios (exports increase by 35% and 23% in the poverty and prosperity scenario, respectively).

In Australia, which covers most of Pacific OECD, average yields decrease, and yield decreases can be seen in almost all cells (Figure 33 in the Appendix). On the other hand, climate change does have a

widely positive impact on water availability (Figure 34 in the Appendix), thus enabling Australia to extend irrigated agriculture. The higher yields which result from increased irrigated production compensate the increase in overall costs and lead to a decrease in Costs of Food.

Production stays about constant in Pacific Asia in both socioeconomic scenarios under climate change: yield decrease is compensated in the poverty scenario by land expansion (11%), and in the prosperity scenario by investments in technical change, which are 16% higher than without climate change, but cannot completely compensate yield decreases which are still 3% lower than without climate change, leading to an increase in Costs of Food. In the poverty scenario, Costs of Food can decrease because the production of expensive crops is substituted by cheaper crops such as maize and cereals. The highly negative impact of climate change on Costs of Food in Centrally Planned Asia in the poverty scenario is due to restricted trade; while Centrally Planned Asia is able to buffer yield decreases in the prosperity scenario by increasing imports by 25%, in the model no additional imports are possible in the poverty scenario.

While the climate change impact on Costs of Food is regionally very diverse, Costs of Food at the global average do not increase in the prosperity scenario and increase by 9% in the poverty scenario. The increase of Costs of Food in the poverty scenario is due to the high impact of climate change on Costs of Food in Centrally Planned Asia, where 17% of global food production takes place.

While Costs of Food decrease on average in all developed regions (Europe, North America, Pacific OECD), they increase partially in some countries. While this increase is due to yield decreases in Australia, it results from yield increases in Canada, Finland and Norway (Figure 33 in the Appendix) where increased production or new production is now possible, leading to higher Costs of Food (Figure 36 in the Appendix). In addition to the countries that we have already discussed above, Mexico, Brazil, Uruguay, Argentina, Chile, Colombia and parts of China are impacted by increases in Costs of Food. Also in Mongolia and Kazakhstan Costs of Food rise, but here again this can be explained by the positive effect of climate change on yield and production (Figure 33 and Figure 35).

3.5.2 Assessing global agricultural vulnerability

Figure 13 shows a global map of the Agricultural Vulnerability Indicator. While in the prosperity scenario it is only in Latin America that people are slightly affected by climate change as well as exposed to hunger, in the poverty scenario the number of regions falling into the most extreme categories of the Agricultural Vulnerability Indicator are clearly higher. In small areas in the western part of China, in Peru, Bolivia as well as Cambodia and Vietnam people are highly impacted by climate change as well as suffering seriously from hunger.

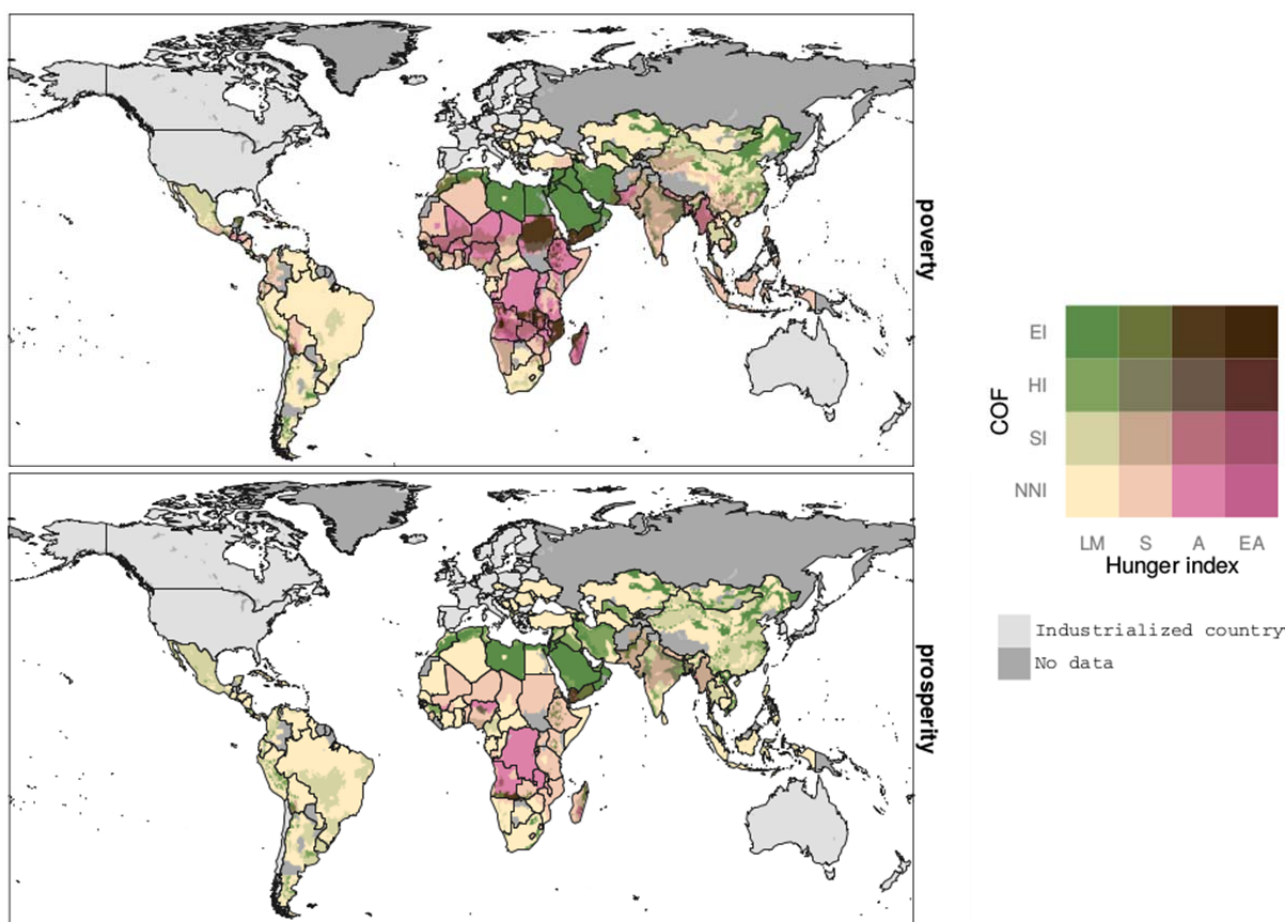


Figure 13: Agricultural Vulnerability Indicator (global coverage) based on the differences of Costs of Food (COF) between RCP8.5 and a no climate change scenario (climate change - no climate change), combined with the projected Vulnerability to Hunger Index for the year 2030 for the two socioeconomic scenarios. (Hunger levels: EA = extremely alarming, A = alarming, S = serious, LM = moderate and low, Climate change impact categories: EI = extremely high impact, HI = high impact, SI = strong impact, NNI = no negative impact; Region names: MNA = Middle East and North Africa, SAS = South Asia, SSA = Sub-Saharan Africa.)

In the poverty scenario 367M people outside the regions Middle East and North Africa, South Asia and Sub-Saharan Africa are exposed to hunger and impacted negatively by climate change through changes in Costs of Food. In Centrally Planned Asia and Latin America the percentage of the population suffering under climate change and hunger is relatively small (6% and 8%, respectively), but 37% of the population in Pacific Asia are affected (Table 8 and Figure 37 in the Appendix).

3.6 Looking beyond 2030

3.6.1 Until 2080 Costs of Food will increase in all three focus regions

Climate change will not stop in 2030. In fact, the consequences of an RCP8.5 world can only be seen to the full extent towards the end of the century. Figure 14 shows the average differences in yields and Costs of Food resulting from climate change, comparing 2030 to 2080. According to model results, average yields decrease in all regions in 2080 compared to 2030 by at least 22%. Costs of food increase in all regions and scenarios beyond 2030.

Here again, the increase is highest in Middle East and North Africa, where Costs of Food increase by 765% in the poverty scenario compared to 35% in 2030 and by 140% in the prosperity scenario compared to 17% in the poverty scenario. While the region is already in 2030 at its limits of expanding agricultural area or increasing imports, the situation is aggravated in 2080, leaving only massive (and rather unrealistically high) investments in technical change as an option to guarantee sufficiently high yield levels to fulfil domestic food demand. In our model, the situation is indeed so extreme that agricultural R&D investments in the poverty scenario in 2080 are 119 times higher with climate change than without climate change (compared to twice as high in 2030). Due to a lower population in the prosperity scenario (540M people compared to 715M people in the poverty scenario), the necessary increase in technical change investments is here only 11 times higher with climate change compared to a no climate change world.

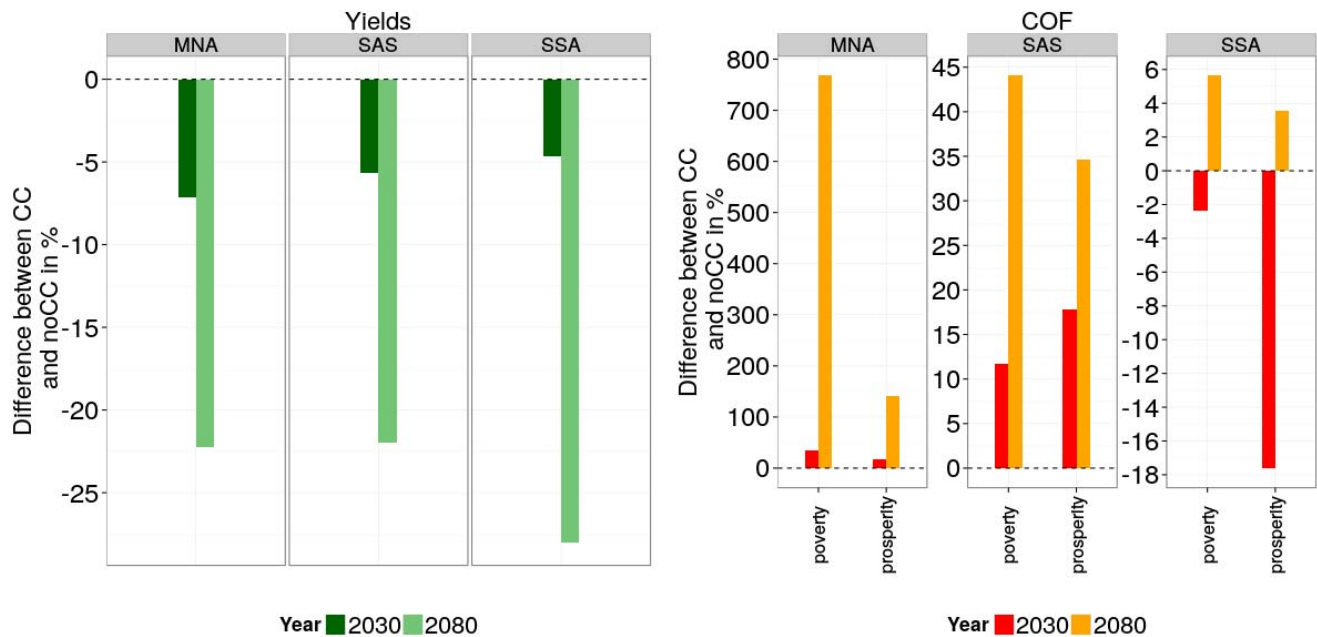


Figure 14: Regional average difference in biophysical yields of food crops (left panel), and Costs of Food (COF) (right panel) for RCP8.5 compared to a no climate change scenario (climate change - no climate change), for two socioeconomic scenarios and for the years 2030 and 2080. (Region names: MNA = Middle East and North Africa, SAS = South Asia, SSA = Sub-Saharan Africa.)

In South Asia, too, Costs of Food increase under climate change in 2080 by 44 % in the poverty scenario and 35% in the prosperity scenario, where the impact of climate change on Costs of Food is mitigated through expansion of agricultural land (by 7% in both socioeconomic scenarios) and changes in trade flows. Here again, the decisive difference between the socioeconomic scenarios is the trajectory of population growth. While in 2080 in the prosperity scenario 1903M people are projected to live in South Asia, this number is 2292M in the poverty scenario. Whereas the production of feed crops for exporting was an important driver of Costs of Food in 2030 in the prosperity scenario, crop yields are likely to become worse compared to the other regions in 2080, and feed crops as well as livestock production decrease under climate change in 2080.

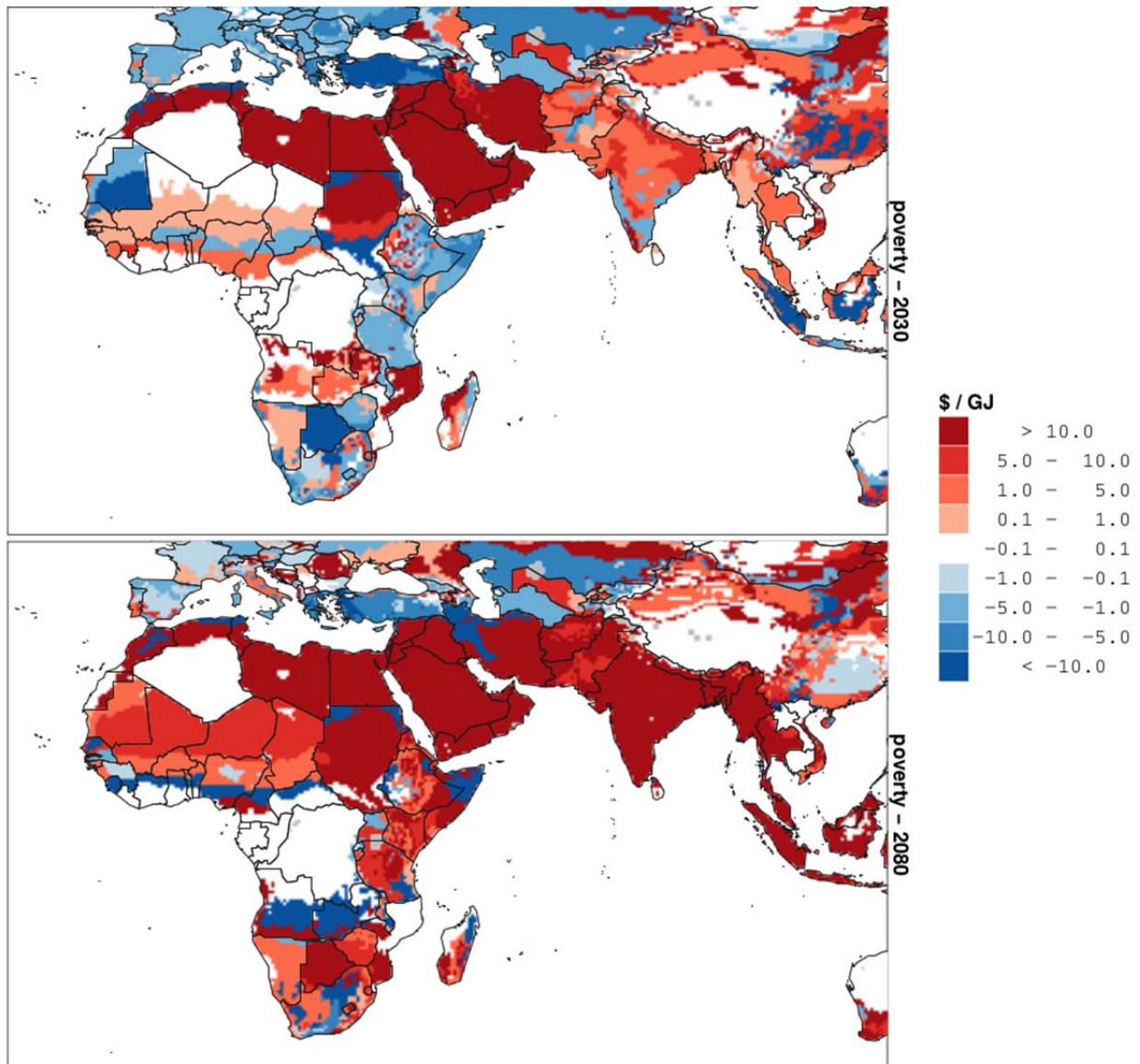


Figure 15: Cellular average difference in Costs of Food for 2030 and 2080 for RCP8.5 and the poverty scenario compared to a no climate change scenario (climate change - no climate change). Positive values (red) indicate that Costs of Food increase, while negative values (blue) show that Costs of Food decrease.

Compared to 2030 where Costs of Food decrease in both socioeconomic scenarios, Costs of Food increase in Sub-Saharan Africa by 6% in the poverty scenario and 4% in the prosperity scenario under climate change in 2080. Although percentage changes are similar, they are generated through different socioeconomic conditions. In the prosperity scenario, a relatively low population of 1700M people has to be fed. Additionally, Sub-Saharan Africa can adapt to climate change by decreasing exports and increasing imports by 3148PJ, thus even being able to decrease agricultural area by 10% and keeping overall costs about constant. In the poverty scenario, 1263M more people are living in the region and trade is more restricted, creating the necessity to increase agricultural area by 10% with climate change and increasing overall production costs by 18%. The pressure on the supply side through climate change impacts can be alleviated in the model by almost completely giving up export production of feed and livestock products.

Figure 15 shows at a spatially explicit level how Costs of Food change under climate change. While in 2030 many countries are positively affected by climate change, especially in the eastern part of Sub-Saharan Africa, positive effects of climate change on Costs of Food are an exception in 2080, limited to some parts in Angola, Zambia, Somalia, South Africa, Morocco, Algeria and a narrow band south of the Sahel.

3.6.2 The number of people negatively impacted will increase in the very long term

While, due to a lack of poverty projections until 2080, we are not able to make good projections about the impact of climate change on people vulnerable to hunger, we can estimate the total number of people potentially affected by climate change based on our data set on spatially explicit population. But it should be mentioned here again that our population projection are based on the assumption that the spatial population distribution remains the same over time, thus possibly neglecting an important adaptation option, namely migrating to more favorable regions. The difference between the total number of people affected in 2030 and 2080 is especially high in Sub-Saharan Africa. While in 2030, 26% of the regional population is likely to be strongly, highly or extremely highly impacted in the prosperity scenario, 64% may be impacted in these categories in 2080. In the poverty scenario, 45% could be at least strongly impacted in 2030, compared to 58% in 2080. In South Asia, the percentage of the affected population may increase from 82% in the poverty and prosperity scenario in 2030 to 99% (the poverty scenario) and 97% (the prosperity scenario) in 2080. In Middle East and North Africa, the percentage of affected people may rise in the poverty scenario from 87% in 2030 to 89% in 2080 and in the prosperity scenario from 76% in 2030 to 98% in 2080.

While the positive economic development in the prosperity scenario may be able to buffer some of the negative effects of climate change until 2030, our results indicate that detrimental climate impacts could outpace economic advances in 2080. More people may be impacted in Middle East and North Africa in the prosperity scenario, because more people are concentrated in areas which are affected by climate change.

In 2080, global average Costs of Food could more than double (plus 131%) under climate change in the poverty scenario and increase by half in the prosperity scenario, compared to no increase in the prosperity scenario in 2030 and an increase of 9% in the poverty scenario. The absolute number of people affected by strongly increasing Costs of Food will be 6,929M in the prosperity scenario and 9,128M in the poverty scenario. A large share of these people will live in developed countries and are likely to cope easily with increases in Costs of Food. Another part of the global population, living in developing countries, will hopefully be lifted out of poverty by then. Nevertheless, it is clear that many people will still be vulnerable to hunger and will be affected by severe consequences of climate change in the more distant future.

4 Conclusions

4.1 Main findings

We combine the spatially explicit Vulnerability to Hunger index with climate-induced increases in Costs of Food to analyze the effects of climate change on people exposed to hunger in the three most vulnerable global regions: Middle East and North Africa, Sub-Saharan Africa, and South Asia. While projected trends of the Vulnerability to Hunger index and the ability to adapt reflect the possible positive impact of economic growth, increases in Costs of Food show that economic development can be offset by climate change.

Our results show that agriculture in the *Middle East and North Africa* is severely affected by climate change, but that the projected economic growth in this region is likely to alleviate Vulnerability to

Hunger. Problems may grow if development is slower than expected and negative effects of climate change cannot be offset. Due to limited adaptation options such as expanding land or importing food, our model resorts to unrealistically high investments in technical progress, showing the huge challenge of this region with regard to feeding its population. Even if such investments were possible they would not only be positive, as scarce financial resources could then not be used for education, infrastructure or similar important development enhancing measures. Solving this unprecedented challenge may require substantial changes in the established economic system.

Egypt, for example, which has long focused on food self-sufficiency and subsidized farmers as well as constrained imports by setting specific quality standards, is now thinking about easing the latter (Daily News Egypt, 2014). In the long term, massive increases in food imports or even increased out-migration might be necessary as part of the solution.

Until 2030, adverse impacts of climate change on Costs of Food remain limited in *Sub-Saharan Africa*, while hunger is still prevalent due to relatively low economic growth. But even if Sub-Saharan Africa is able to adapt over the next two decades, large parts of this region will be negatively affected by climate change by 2080.

In *South Asia*, only a small number of people are extremely or highly impacted by climate-induced increases in Costs of Food, while at the same time falling into an alarming or extremely alarming hunger category. However, 81% (poverty scenario) and 59% (prosperity scenario) of the population are at least strongly impacted by climate change and at least seriously vulnerable to hunger (Table 5). Although an extreme combination of Vulnerability to Hunger and negative climate change impacts seems to be avoidable in the short run, the large number of people affected should raise the awareness of policy makers.

While the impact of climate change on poor people is already very clear in 2030, the consequences will be much more severe by 2080. Not only will the number of countries and people negatively affected increase, but the Costs of Food are also projected to grow further. Furthermore, our results indicate that adaptation measures such as trade liberalization or shifting production to more productive areas will be less effective in 2080, since a significantly larger share of global agricultural land will be negatively impacted by climate change. With regard to socioeconomic indicators, trade liberalization has the most decisive impact on regional Costs of Food, either by decreasing them (through more imports and less exports) or by increasing them (through more exports, e.g. of feed and livestock). This does not imply that the other relevant settings, namely GDP-dependent dietary patterns and population change, do not matter. But in our specific implementation of the two socioeconomic scenarios (the poverty scenario with high population and low GDP growth; the prosperity scenario with low population and high GDP growth), the effect of higher population and food demand in the poverty scenario is largely offset in the prosperity scenario through higher income and resulting per capita calorie and livestock demand.

Trade liberalization is an important adaptation mechanism and can reduce the Costs of Food globally. However, our results show that the effects of trade liberalization can have also some negative local effects. In *South Asia*, trade liberalization may increase Costs of Food since the region in our model specializes in feed and livestock production for exports to developed regions, at the expense of production satisfying local consumption needs.

Looking at the other two adaptation options analyzed in this study, it is quite clear that investing in technical progress alleviates the negative impacts of climate change on Costs of Food in all focus regions, while in the case of improving market access the positive effect is less obvious. It gives poor farmers the opportunity to extend production to previously unused land in the Middle East and North Africa, as well as in *South Asia*, thus improving their income. But it may lead to increased Costs of Food for local consumers by 40% in Middle East and North Africa and 50% in *South Asia*. Despite this regional increase in Costs of Food, at the global level consumers will benefit from overall lower world market prices.

4.2 Policy implications of this study

- 1.) Similarly to previous studies (e.g. FAO, 2013), our results emphasize that economic development is a straightforward way to reduce the number of people exposed to hunger and rising Costs of Food due to climate change. High GDP growth, accompanied by a slowly growing population and liberalized trade as in the prosperity scenario can reduce both the negative impacts of climate change on the Costs of Food and the number of people vulnerable to hunger.
- 2.) Policy support for technical progress in agriculture, such as the development of new crop varieties and production techniques which are better adjusted to changing climatic conditions and more robust towards climate variability, have to play an important role. This has to be accompanied by adequate training for farmers. Case study evidence shows that simply subsidizing the price of fertilizers, which is a frequent practice in many countries, often leads to fertilizer overuse, soil salinization and pollution of surface and groundwater aquifers (Wang et al., 2013). Continuous public investments into agricultural R&D as well as extension services are urgently required and have already revealed high social rates of return in the past. To support developing countries in this respect, international funds could be raised through the potential revenues from a global GHG emission trading scheme.
- 3.) Improving market access creates the opportunity for poor farmers to extend production into more remote areas and facilitates exporting to other countries. While this increases revenues for farmers, local consumers in some regions may suffer from increases in Costs of Food. Improving infrastructure in order to boost economic growth is therefore important, but interests of local consumers should be taken into account.
- 4.) Taking advantage of the variation of climate-induced yield changes across space and between species, especially until 2030, production can be profitably shifted to more productive areas, as well as higher yielding crops. Therefore, farmers should be trained in adopting new varieties and switching to more suitable crop species, if appropriate. Adopting mixed cropping systems instead of monocultures may reduce the risk of total crop failure in a more variable climate.
- 5.) Trade liberalization is one of the most important adaptation mechanisms. However, our results show that trade liberalization could have some negative local effects. In such regions, international trade liberalization should be accompanied by national policy measures, e.g. food aid or favorable terms for agricultural exports, as already agreed upon in the Marrakesh decision on “Measures Concerning the Possible Negative Effects of the Reform Programme on Least-Developed and Net Food-Importing Developing Countries” which was signed in the Uruguay round in 1994.
- 6.) Insurance schemes like crop insurance or income stabilization programs can provide compensation for crop and property damages caused by climate-related hazards like droughts or floods. However, insurance in developing countries is only available to a very limited extent. In India, the National Agriculture Insurance Scheme was implemented to protect farmers against losses due to crop failure caused by drought, flood, hailstorm, cyclone, fire, pests and diseases. All food crops, oilseeds and annual commercial and horticultural crops are covered. However, only 4% of farmers are currently protected by the crop insurance scheme (Bhise et al., 2007).
- 7.) There is robust evidence (Behrman et al., 2004; Foster and Rosenzweig, 1993; Glick and Sahn, 1998; Hoddinott, 2006; Clarke and Hill 2013) showing that suffering hunger at a young age decreases peoples’ live-time earnings as well as education and employment opportunities. In the areas hit hardest by negative climate impacts, international efforts should therefore concentrate on providing food especially for young children, as well as possibly on supporting migration of most vulnerable households from these territories.

- 8.) The negative long-term consequences of climate change by 2080 will increase the Costs of Food in almost all countries in the developing world. Hunger is likely to increase despite the alleviating effects of economic growth. Therefore, in addition to effective adaptation strategies, it is crucial to implement ambitious GHG mitigation measures, in order to keep climate impacts manageable.

4.3 Limitations of the model and the study approach

While our modeling results give an indication on how future climate change could impact people suffering from hunger, there are clearly some limitations. High increases in Costs of Food in Middle East and North Africa should give rise to concern. It shows that a small region severely hit by climate change, with no additional agricultural land available and relatively closed economies, will have difficulties to adapt. But the results of our study should be seen in the context of the limited possibilities the model can explore. The assumption that agricultural R&D may take yield levels far beyond pre-climate change observations may be unrealistic. It can also be assumed that, in extreme cases, the structure and levels of food imports may change substantially in the future, which may not be reflected in our current model. Restricted substitutability of crops in the model may lead to an exaggerated demand for low yielding temperate cereals in the Middle East and North Africa, while high yielding tropical cereals are even exported. This partly explains the extreme increase of Costs of Food in this region. The fact that investments in technical change lead to an overall yield increase for all crops might also be questionable since in practice R&D is often targeted toward one crop only. And, finally, a region like Middle East and North Africa will probably not be able to afford such immense investments in yield increasing technical change, which shows that the risk of hunger in such a situation is very high.

An important adaptation option observed in our study, namely the shifting of crops to more productive areas, particularly in Sub-Saharan Africa, should also be considered with caution. Land already used for agricultural production can without any additional costs be utilized for the production of any other crop. However, in reality, changing e.g. from growing temperate cereals to fruits or vegetables may require different equipment and also additional training for farmers. For the costs of cultivating previously unutilized land, the model takes into account the costs of land expansion, such as clearing forests. Transaction costs, e.g. for shifting labor or capital, or costs which are not easily measured in monetary terms, e.g. costs of family migration, are currently not considered. Beside the model simulations itself, also exogenous model inputs, namely the yields and water availability derived from 5 general circulation models are subject to uncertainty, which is visible by the differences in results (Figure 18). Taking the mean of climate model results improves reliability, but still leaves uncertainty as the most reliable model might be underrepresented. Additionally, we use here results without CO₂ fertilization which overestimates the effect of climate change. As mentioned before, the projection of the spatially explicit Vulnerability to Hunger Index into the future based on current spatial distribution is unrealistic, as hot spots of economic prosperity and failure might move. Similar is true for the spatial distribution of population on which the people counts of this study are based. Due to a lack of information the projected patterns of spatially explicit population stays constant, although people will probably move inside or between countries. For our study we have used two extreme climate scenarios, RCP8.5, resulting in an average temperature increase at the end of the century of 3.7°C, and a no climate change scenario. As the latter is highly unrealistic, showing the difference between a climate change and a no climate change scenario might indicate that the effect of reducing emissions is higher than can still be achieved. Another exogenous input which complicates the interpretation of model results are the exogenously given demand trajectories. While it is a very plausible assumption that in a world prone to poverty per capita food consumption is lower than in the prosperity scenario, the resulting lower overall demand leads to less pressure on agriculture. This

effect might lead to an underestimation of the impact of climate change on Costs of Food in the poverty scenario.

4.4 Comparison to the literature

Compared to previous literature estimates, our results provide higher numbers of people prone to poverty, hunger and climate change impacts. To give an example, Shepherd et al. (2013) estimated that 325M people will be living on less than US\$1.25 per day in 2030 in the 49 countries most prone to natural hazards. The most exposed countries to both poverty and natural hazards are, according to that study, located in South Asia and Sub-Saharan Africa. Shepherd et al. (2013) estimated also that in 2030 624M million people will be living on less than US\$1.25 per day in a baseline scenario and 182M million in an optimistic scenario. Parry et al. (2005) furthermore projected that with no climate change 496M people globally will be at risk of hunger in the 2020s and 312M people in the 2050s. Under unmitigated climate change, these numbers would grow to 521-531M in the 2020s and 309-321M people in the 2050s. Similarly to the previous study, Parry et al. (2005) classified Southern Asia and Africa as the most exposed regions to an increased risk of hunger as a result of climate change.

The reason for these differences is our specific study approach, where we have a wide range of intensity levels for both dimensions of the Agricultural Vulnerability Indicator (i.e. changes in Costs of Food and Vulnerability to Hunger). According to this definition, 33% (2867M people) of the global population in the poverty scenario and 18% (1460M people) in the prosperity scenario will be vulnerable to hunger and negatively affected by increases in Costs of Food. If we exclude the least negative categories in both dimensions, global numbers are reduced to 2% of the population in the poverty scenario (156M people) and 1% of the global population in the prosperity scenario (50M people).

The novelty of our approach lies in presenting results at the subnational level. We show that climate change impacts are likely to differ across larger geographical regions, but that they will also be differentiated within national boundaries. Although other studies, similarly to ours, list South Asia and Sub-Saharan Africa as the most exposed regions to the simultaneous impact of poverty and climate hazards (Parry et al., 2005; Shepherd et al., 2013), our projections are more detailed and show areas which are particularly exposed. We can show that the impacts within national boundaries will not be evenly distributed. Even for countries classified by previous studies at the highest risk of disaster-induced poverty, such as Bangladesh, Sudan, Madagascar or Pakistan (Shepherd and et al., 2013), our model indicates that the impacts may be concentrated in certain locations, such as the coastal parts of Bangladesh and northern Sudan. Our projections give a first indication which locations may be at the highest risk of hunger and where the availability of basic resources will be most severely constrained by climate change.

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6 Appendix

6.1 Translation of SSP indicators into model parameters for the non-focus regions

Table 6: Translation of SSP indicators into model parameters and their implementation for the poverty scenario based on SSP4 (all refer to the year 2030). (For the seven non-focus world regions.)

Regions	Centrally Planned Asia	Europe	Former Soviet Union	Latin America	North America	Pacific OECD	Pacific Asia
Population in million people	1484	645	275	675	398	154	598
Kcal per capita per day (based on GDP)	3409	3622	3323	3101	3907	3216	2914
Demand for food crops in PJ (based on population/ GDP)	7594	3297	1339	3031	2271	630	2404
Share of livestock products in the diet (based on GDP)	0.35	0.24	0.27	0.23	0.21	0.16	0.14

Table 7: Translation of SSP indicators into model parameters and their implementations for the prosperity scenario based on SSP5 (all refer to the year 2030). (For the seven non-focus world regions.)

Regions	Centrally Planned Asia	Europe	Former Soviet Union	Latin America	North America	Pacific OECD	Pacific Asia
Population in million people	1491	681	277	650	433	164	588
Kcal per capita per day (based on GDP)	3409	3622	3322	3101	3907	3217	2914
Demand for food crops in PJ (based on population/ GDP)	7594	3297	1339	3031	2271	630	2404
Share of livestock products in the diet (based on GDP)	0.35	0.24	0.28	0.23	0.21	0.16	0.134

6.2 Regression for the spatially explicit Vulnerability to Hunger Index

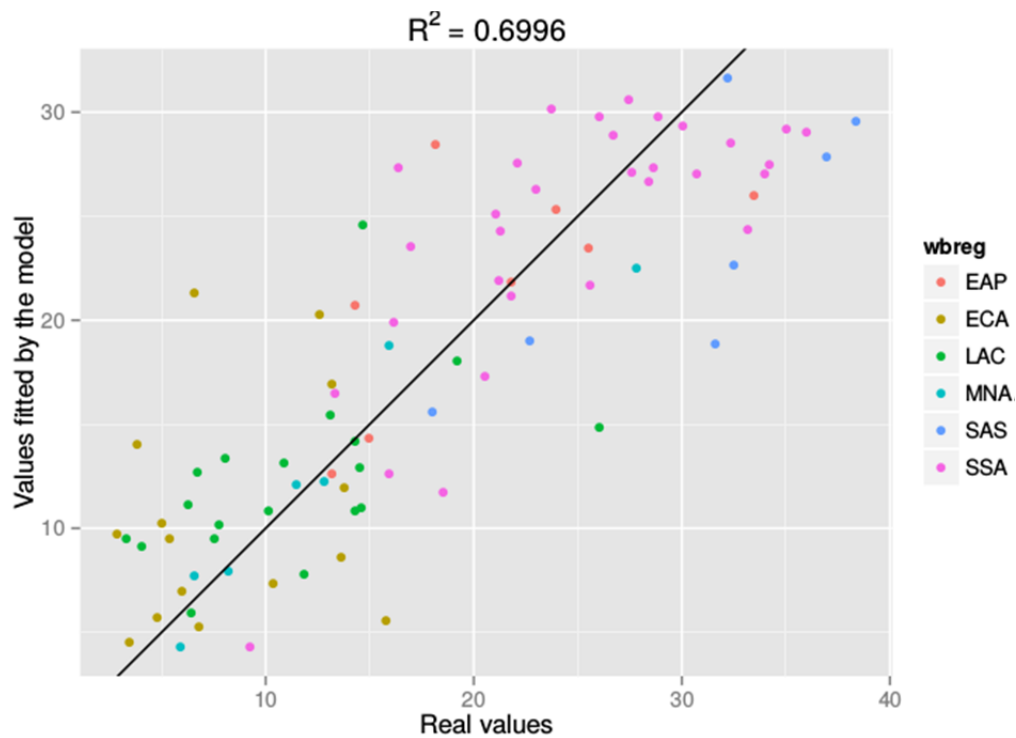


Figure 16: The graph shows the national averages of the spatially explicit hunger index plotted against the fitted values using three sets of economic World Bank projection for the year 2005. The points show the different countries provided in the data set by the World Bank, sorted by the different world regions defined by the World Bank (EAP = East Asia and Pacific, ECA = Europe and Central Asia, LAC = Latin America and Caribbean, MNA = Middle East and North Africa, SAS = South Asia, SSA = Sub-Saharan Africa).

6.3 Difference in projections of the spatially explicit population

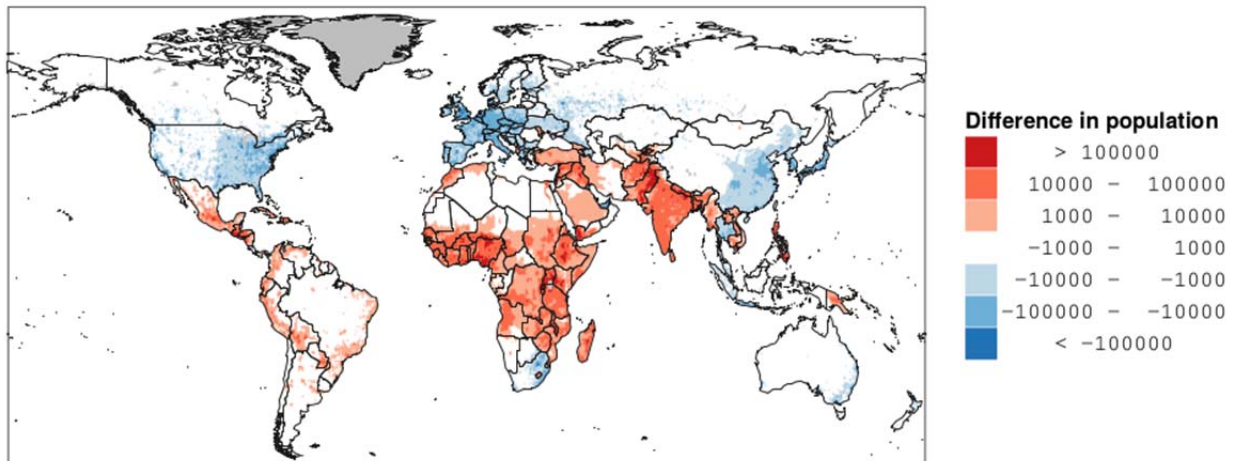


Figure 17: Difference in the projections for the global, spatially explicit population for the year 2030, between the poverty and prosperity scenario based on national population scenarios (International Institute for Applied Systems Analysis (IIASA), 2013) and on a spatially explicit data set of population density (Center for International Earth Science Information Network (CIESIN), Centro Internacional de Agricultura Tropical (CIAT), 2005). We assume that the spatial distribution of population inside countries stays constant over time. Positive values (red) indicate that population is higher in the poverty scenario than in the prosperity scenario, while negative values (blue) show that population is lower.

6.4 Comparison of results for the different general circulation models for 2080, with and without CO₂-fertilization

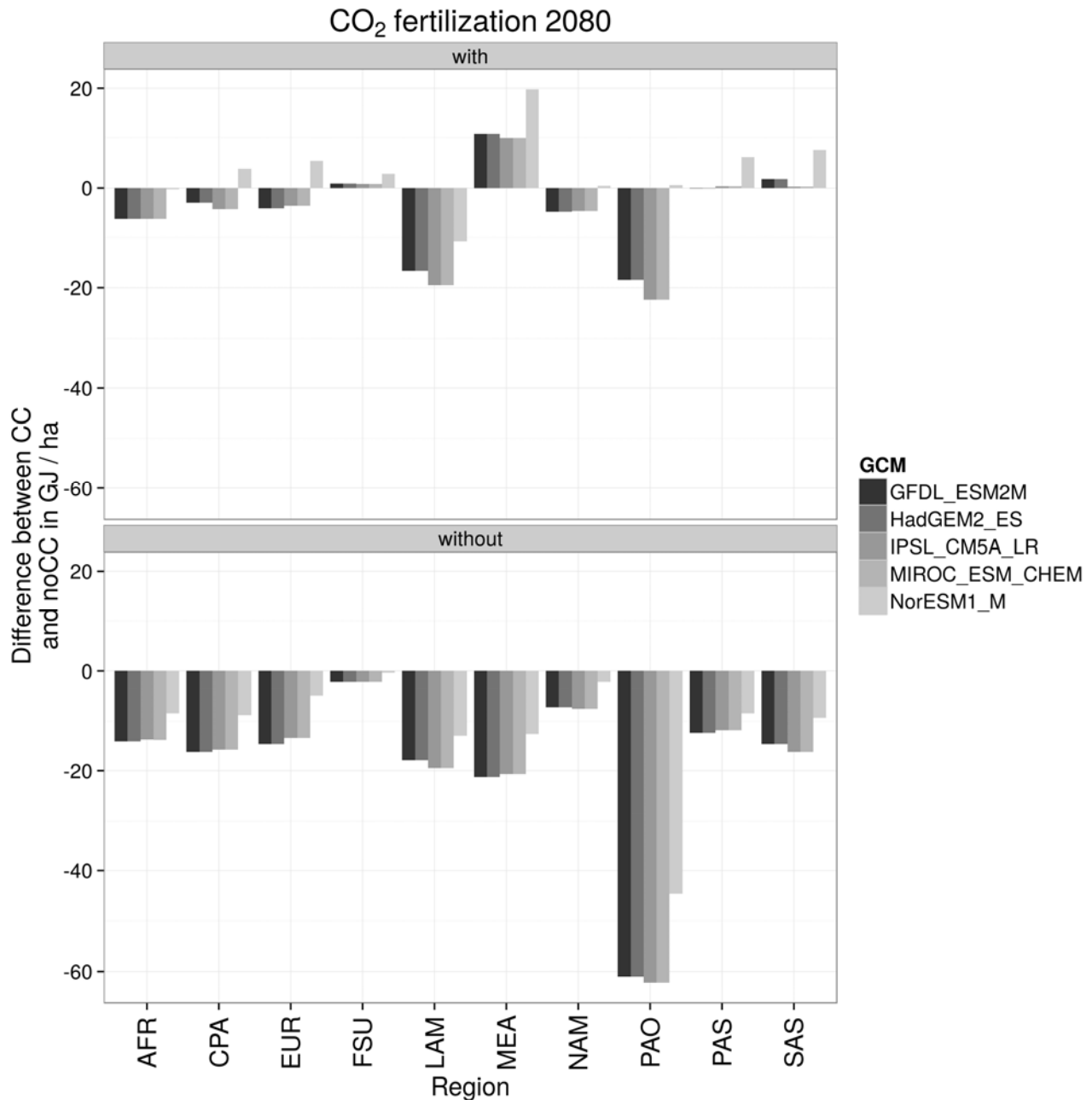


Figure 18: Regional average difference in biophysical yields of food crops for the 5 different general circulation models (GCM) for CO₂ and no CO₂ fertilization for RCP8.5 compared to a no climate change scenario (climate change - no climate change) for the year 2080 and for the 10 MAgPIE regions. (Names of regions in MAgPIE: AFR = Sub-Saharan Africa, CPA = Centrally Planned Asia, EUR = Europe, FSU = Former Soviet Union, LAM = Latin America, MEA = Middle East and North Africa, NAM = North America, PAO = Pacific OECD, PAS = Pacific Asia, SAS = South Asia.)

6.5 Additional indicators: Irrigated and rainfed yields for the focus regions

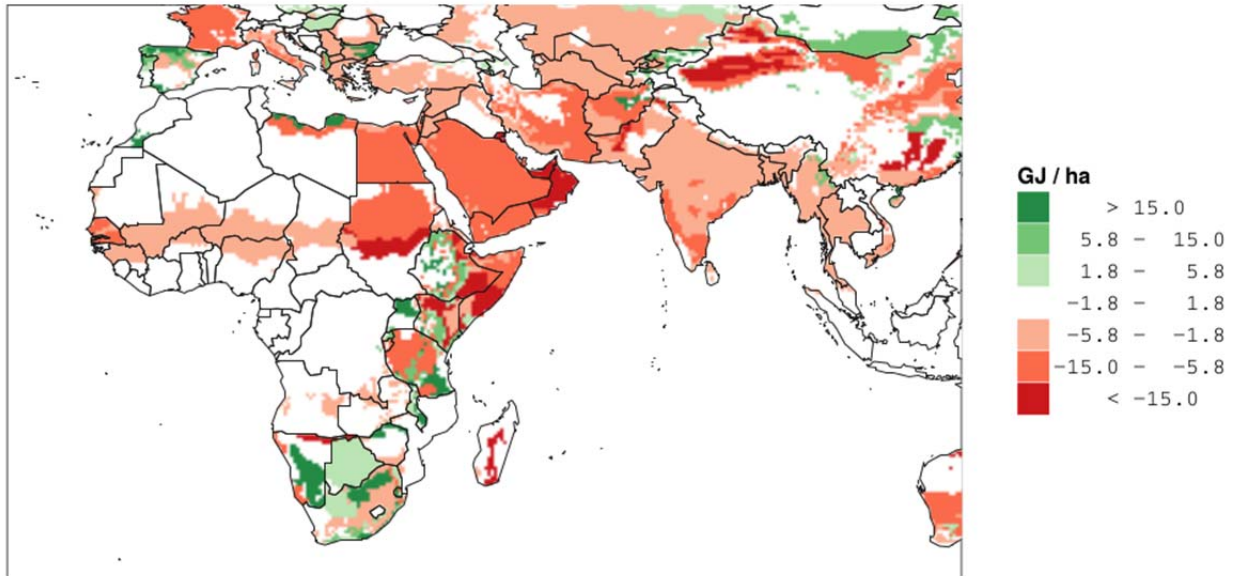


Figure 19: Cellular difference in irrigated yields for food crops in 2030 for RCP8.5 compared to a no climate change scenario (climate change - no climate change). Positive values (green) indicate that yields increase with climate change, while negative values (red) show that yields decrease.

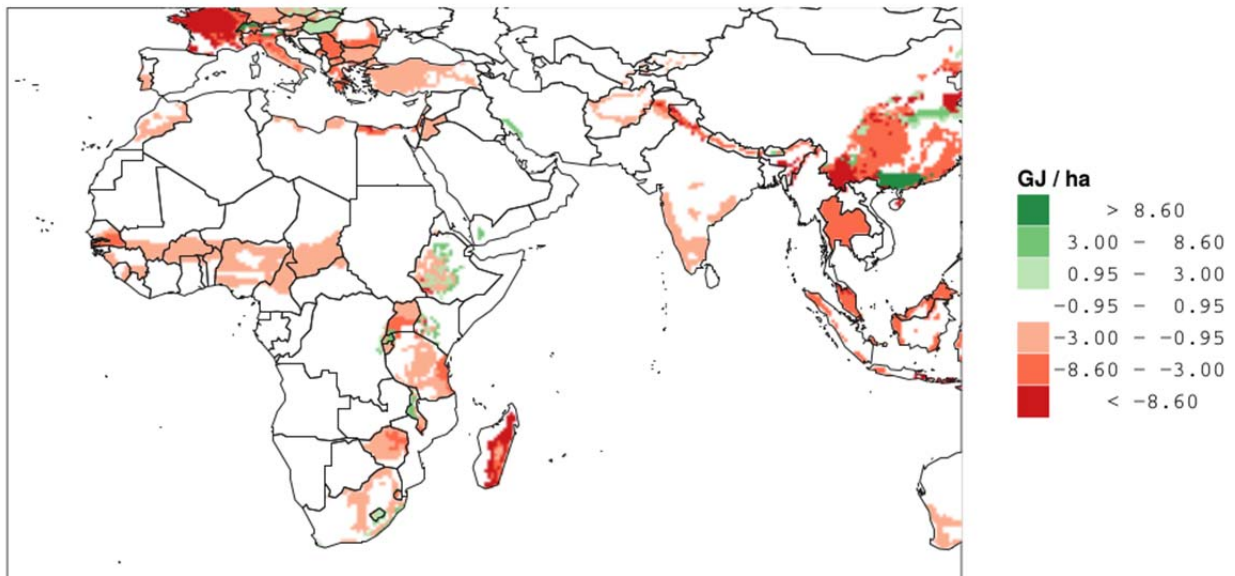


Figure 20: Cellular difference in rainfed yields for food crops in 2030 for RCP8.5 compared to a no climate change scenario (climate change - no climate change). Positive values (green) indicate that yields increase with climate change, while negative values (red) show that yields decrease. (Biophysical results are independent of socioeconomic settings.)

6.6 Regional changes in production, area, trade and costs

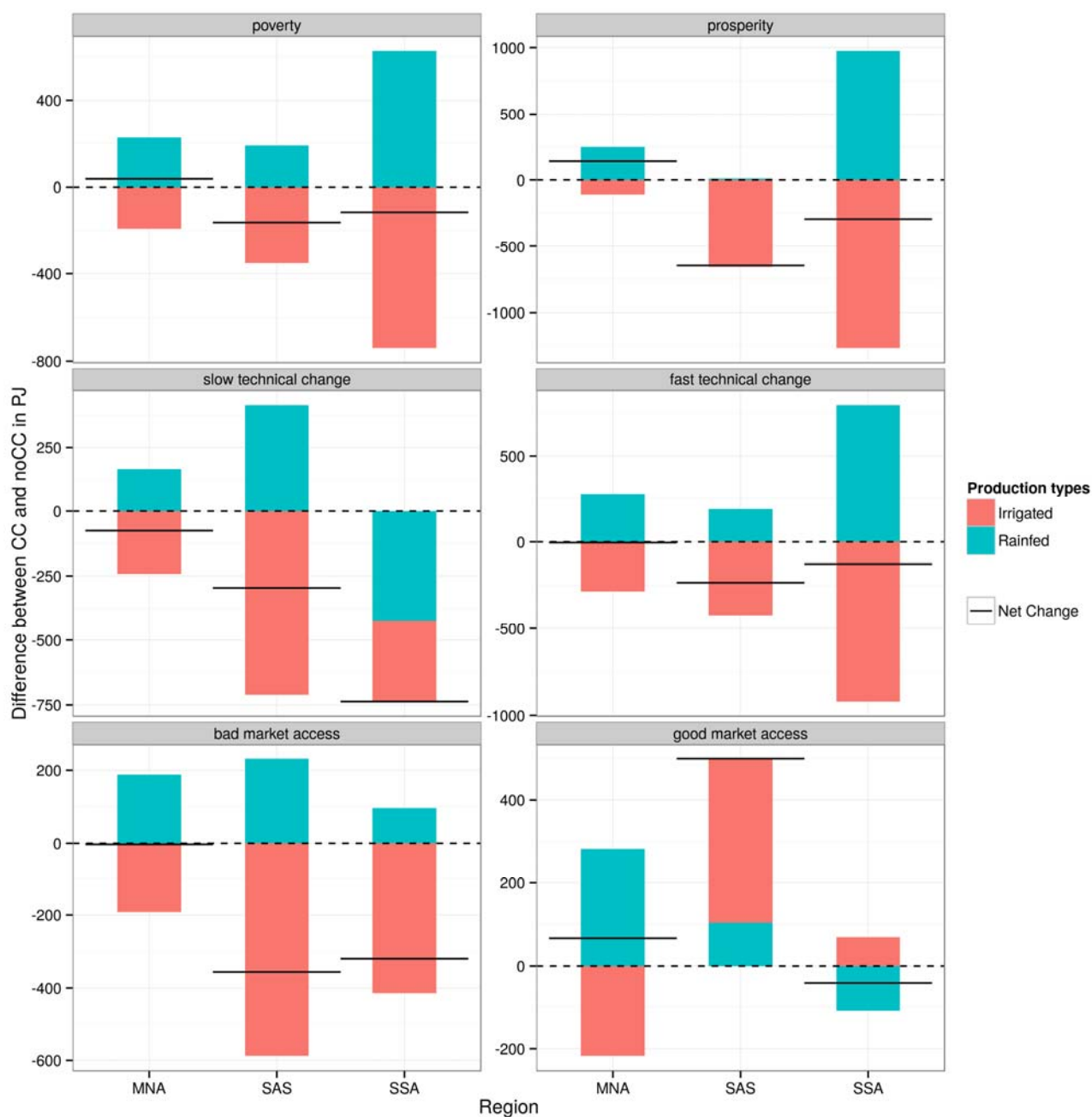


Figure 21: Regional average difference in irrigated and rainfed production of food crops for RCP8.5 compared to a no climate change scenario (climate change - no climate change) for the year 2030, for the three scenario sets. The horizontal black bars show the net change. (Names of the three focus regions: MNA = Middle East and North Africa, SAS = South Asia, SSA = Sub-Saharan Africa.)

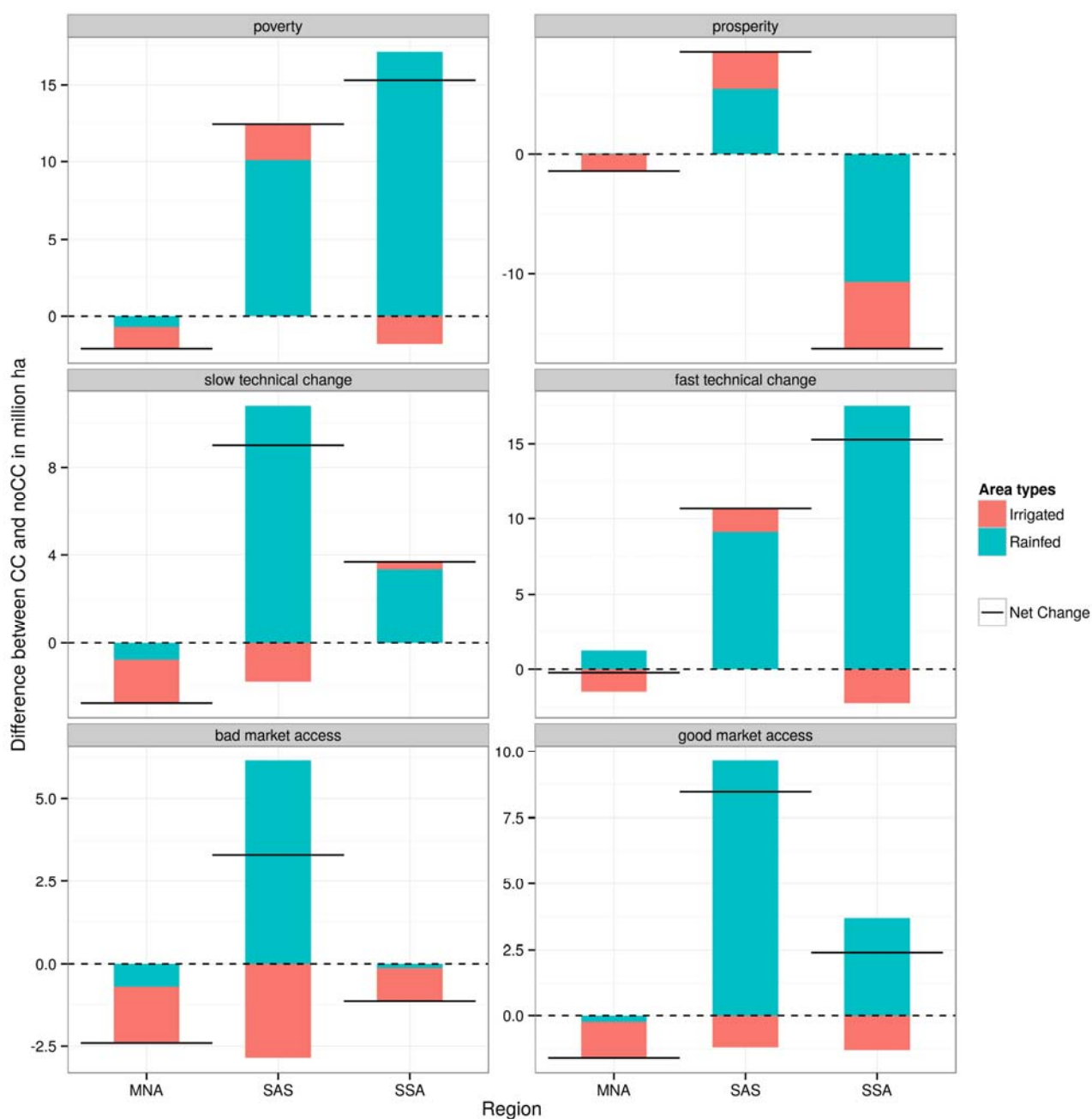


Figure 22: Regional average difference in irrigated and rainfed agricultural area of food crops for RCP8.5 compared to a no climate change scenario (climate change - no climate change) for the year 2030, for the three scenario sets. The horizontal black bars show the net change. (Names of the three focus regions: MNA = Middle East and North Africa, SAS = South Asia, SSA = Sub-Saharan Africa.)

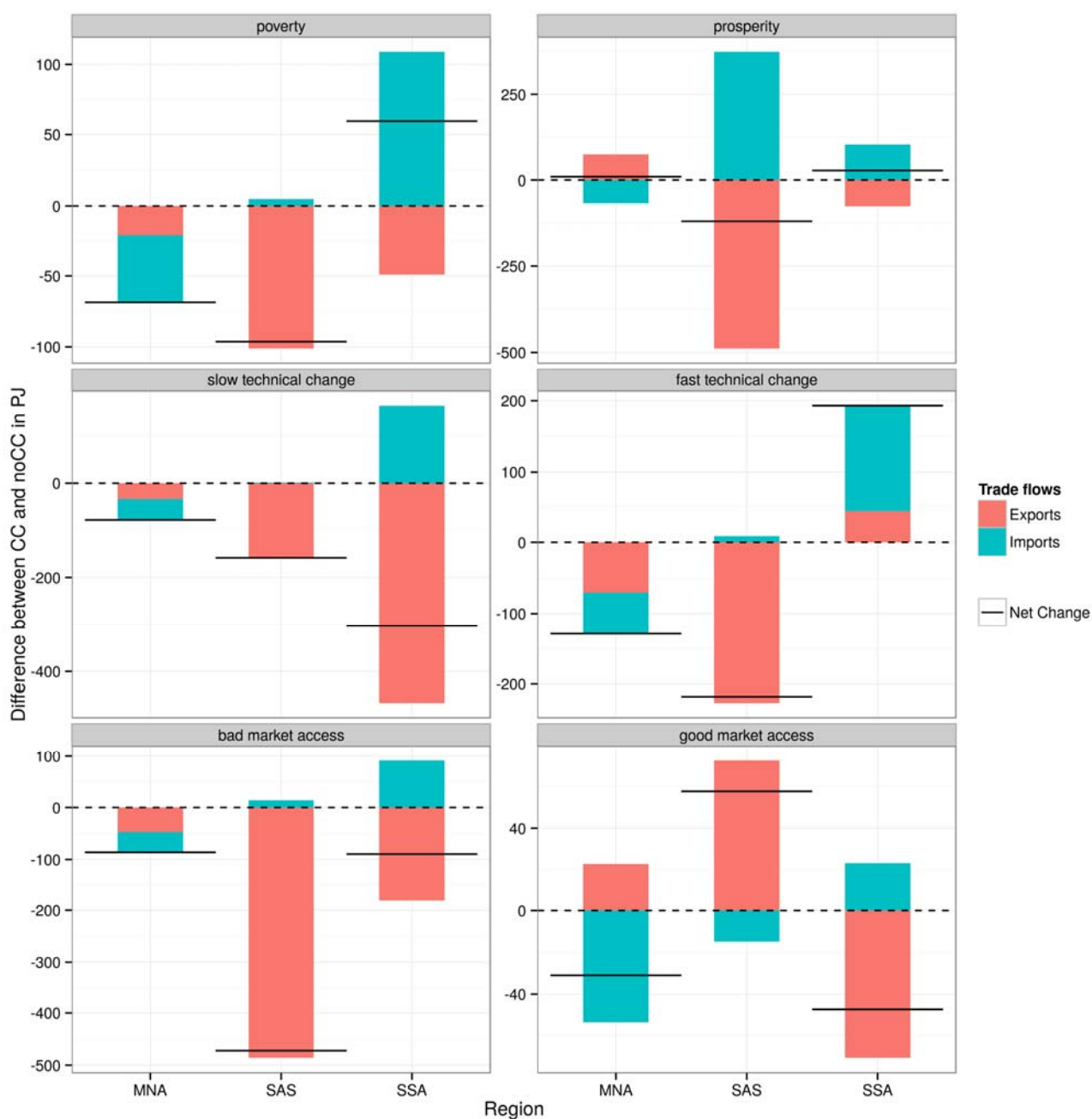


Figure 23: Regional average difference in import and exports of food crops for RCP8.5 compared to a no climate change scenario (climate change - no climate change) for the year 2030, for the three scenario sets. The horizontal black bars show the net change. (Names of the three focus regions: MNA = Middle East and North Africa, SAS = South Asia, SSA = Sub-Saharan Africa.)

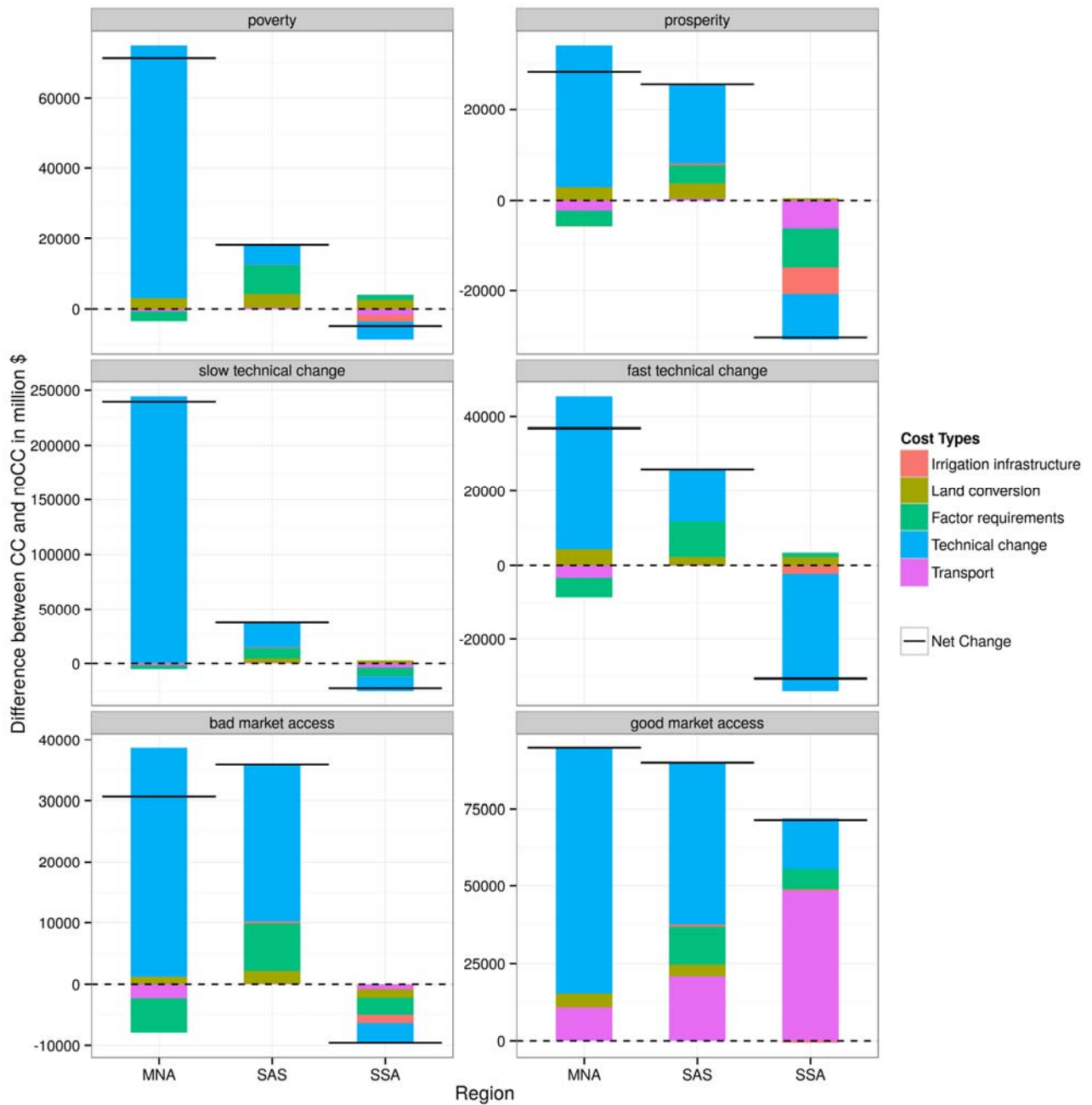


Figure 24: Regional average difference for the different costs types for RCP8.5 compared to a no climate change scenario (climate change - no climate change) for the year 2030, for the three scenario sets. The black horizontal bars show the net change in costs. (Names of the three focus regions: MNA = Middle East and North Africa, SAS = South Asia, SSA = Sub-Saharan Africa.)

6.7 Spatially explicit changes in production, Costs of Food and the Agricultural Vulnerability Indicator for the technical progress scenarios, for the three focus regions

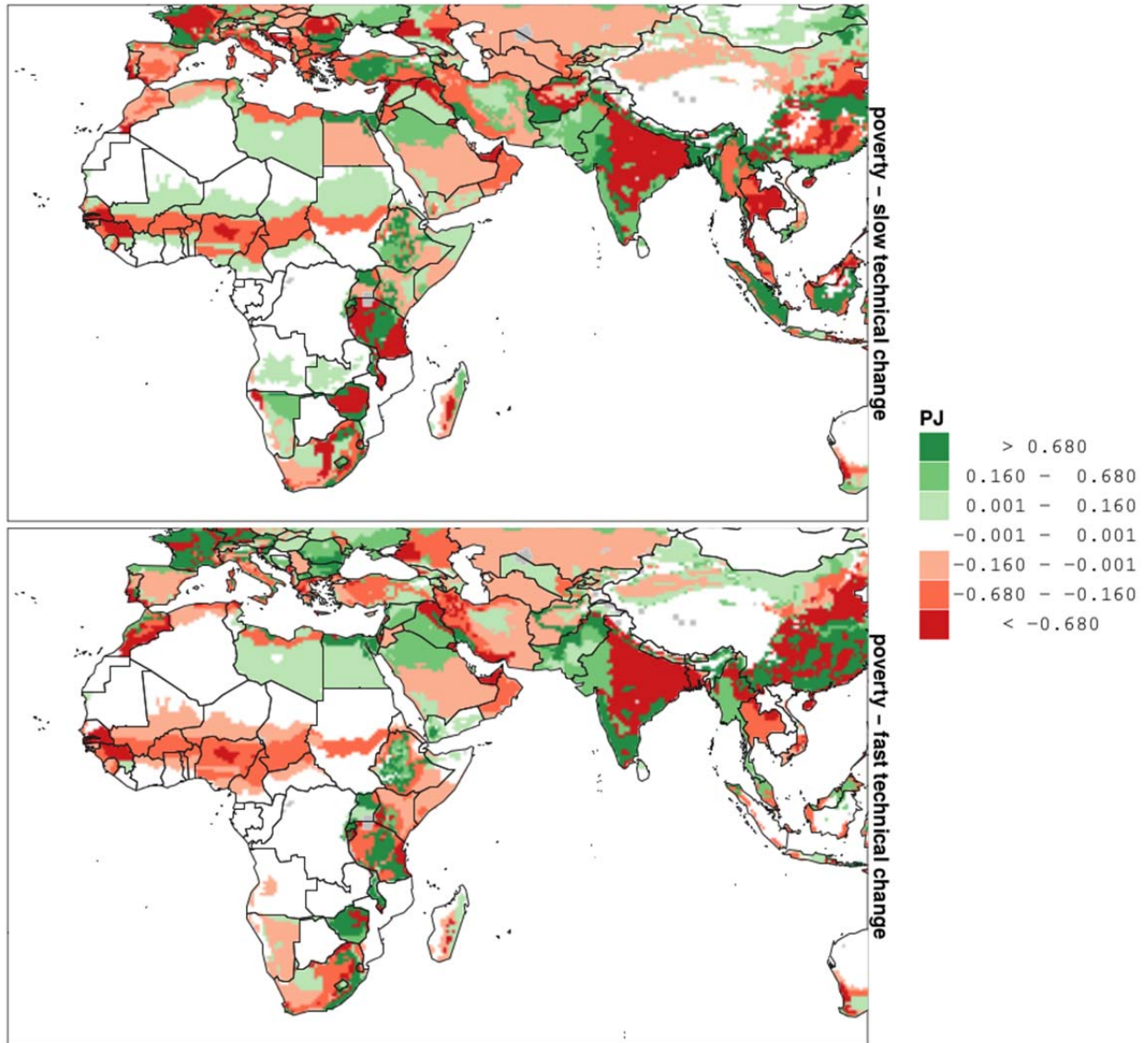


Figure 25: Cellular difference in production of food crops in 2030 for RCP8.5 compared to a no climate change scenario (climate change - no climate change) for two technological development scenarios and the poverty scenario. Positive values (green) indicate that production increases with climate change, while negative values (red) show that production decreases.

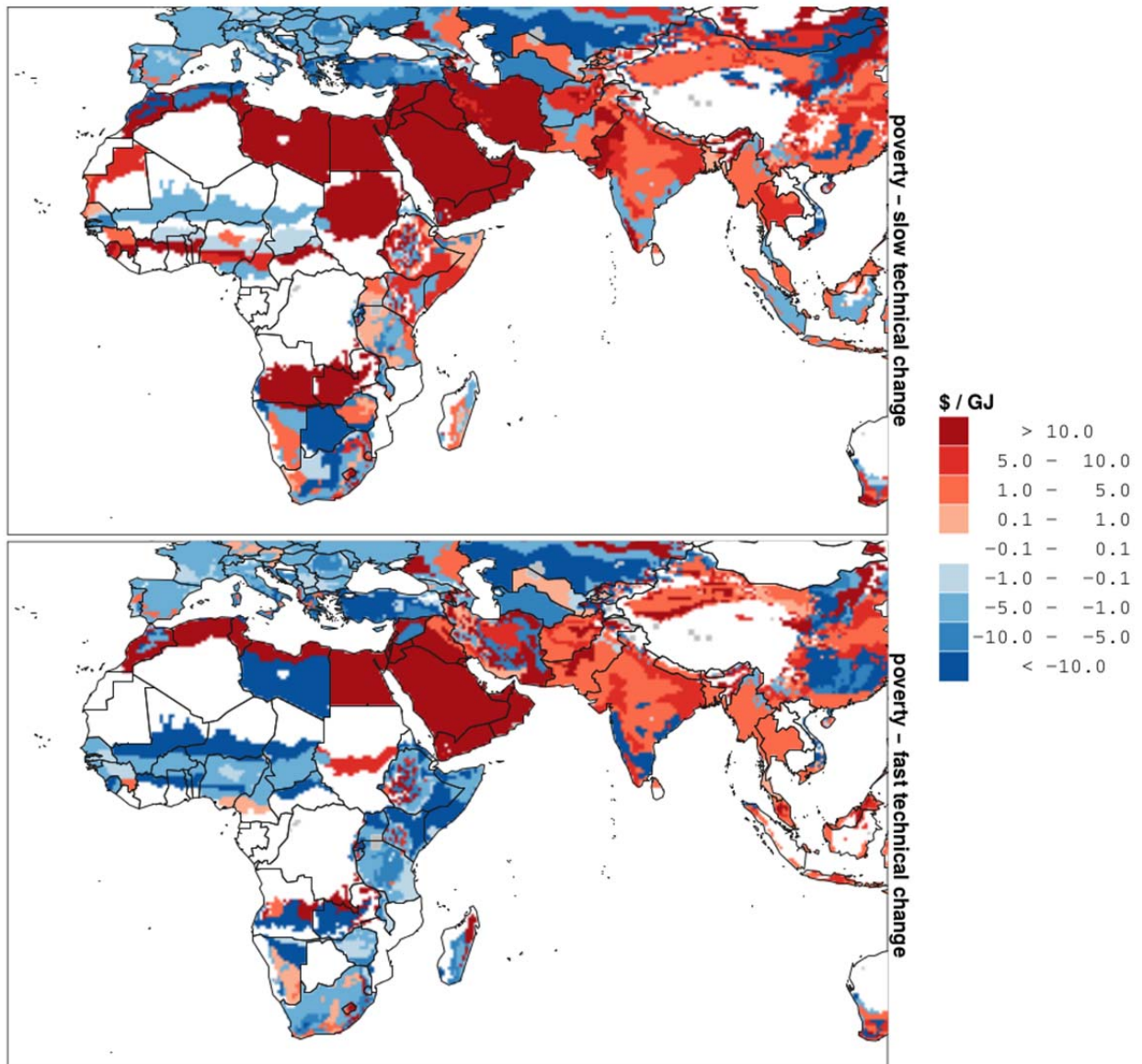


Figure 26: Cellular difference in Costs of Food in 2030 for RCP8.5 compared to a no climate change scenario (climate change - no climate change), for the poverty scenario and for two technological development scenarios. Positive values (red) indicate that Costs of Food increase with climate change, while negative values (blue) show that Costs of Food decrease.

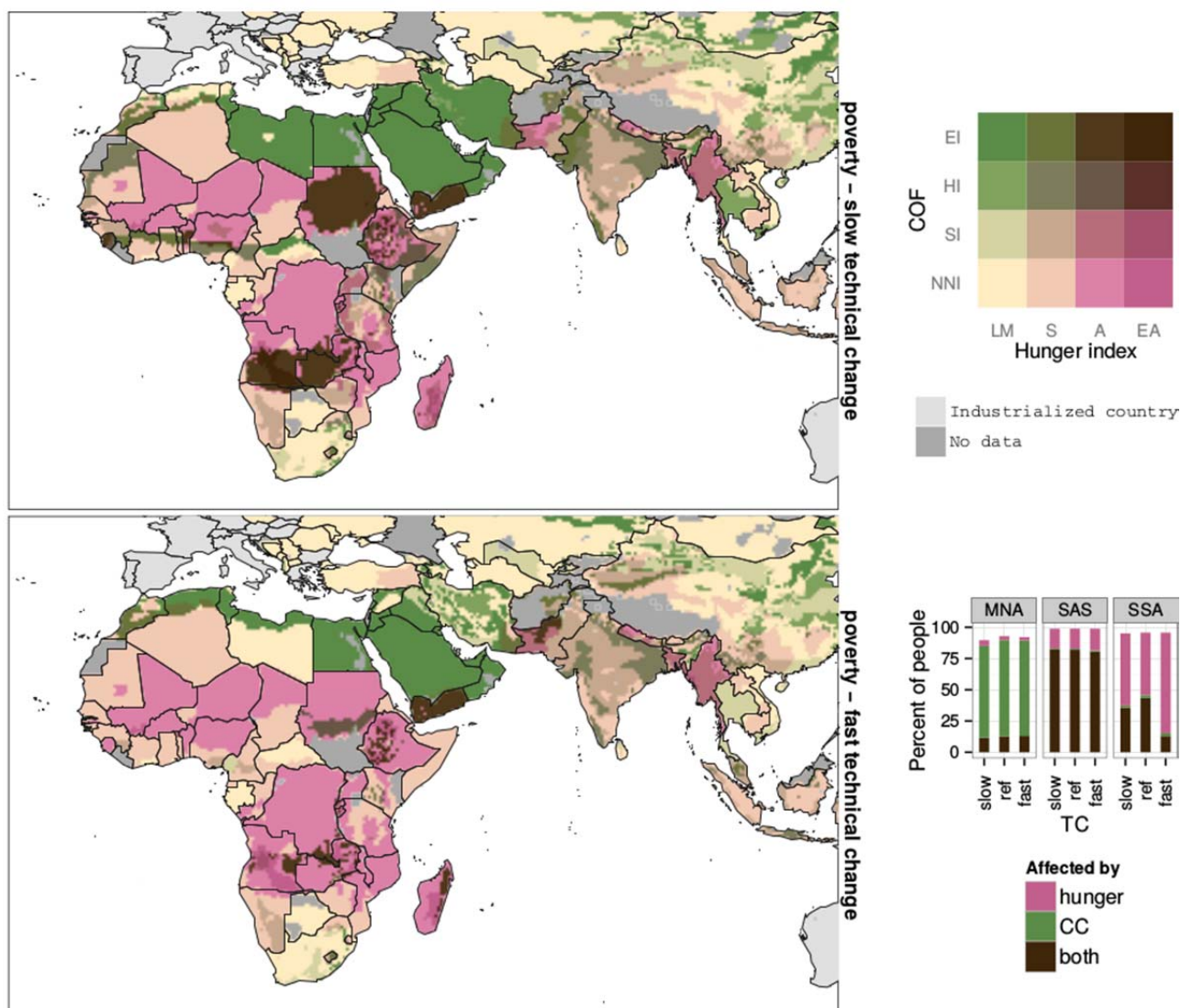


Figure 27: Agricultural Vulnerability Indicator based on the differences of Costs of Food between RCP8.5 and a no climate change scenario (climate change – no climate change), combined with the projected Vulnerability to Hunger Index for the year 2030 for the poverty scenario for two different technological development scenarios (map). Number of people negatively affected by increases in Costs of Food caused by climate change, exposure to hunger and both (barplot).

(Hunger levels: EA = extremely alarming, A = alarming, S = serious, LM = moderate and low, Climate change impact categories: EI = extremely high impact, HI = high impact, SI = strong impact, NNI = no negative impact; Region names: MNA = Middle East and North Africa, SAS = South Asia, SSA = Sub-Saharan Africa.)

6.8 Spatially explicit changes in production, Costs of Food and the Agricultural Vulnerability Indicator for the market access scenarios, for the three focus regions

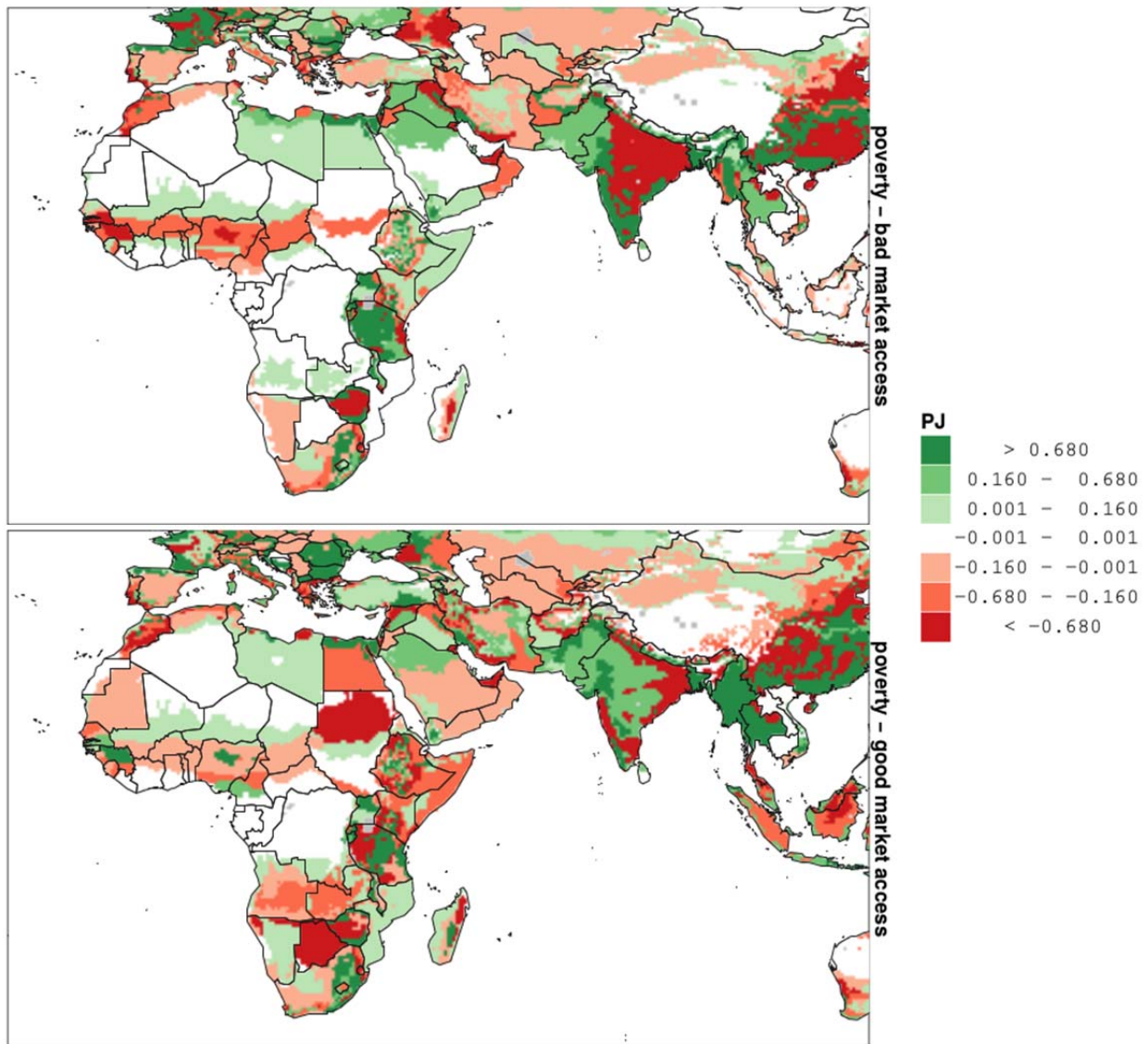


Figure 28: Cellular difference in production of food crops in 2030 for RCP8.5 and a no climate change scenario (climate change - no climate change), for the poverty scenario and two market access scenarios. Positive values (green) indicate that production increases with climate change, while negative values (red) show that production decreases.

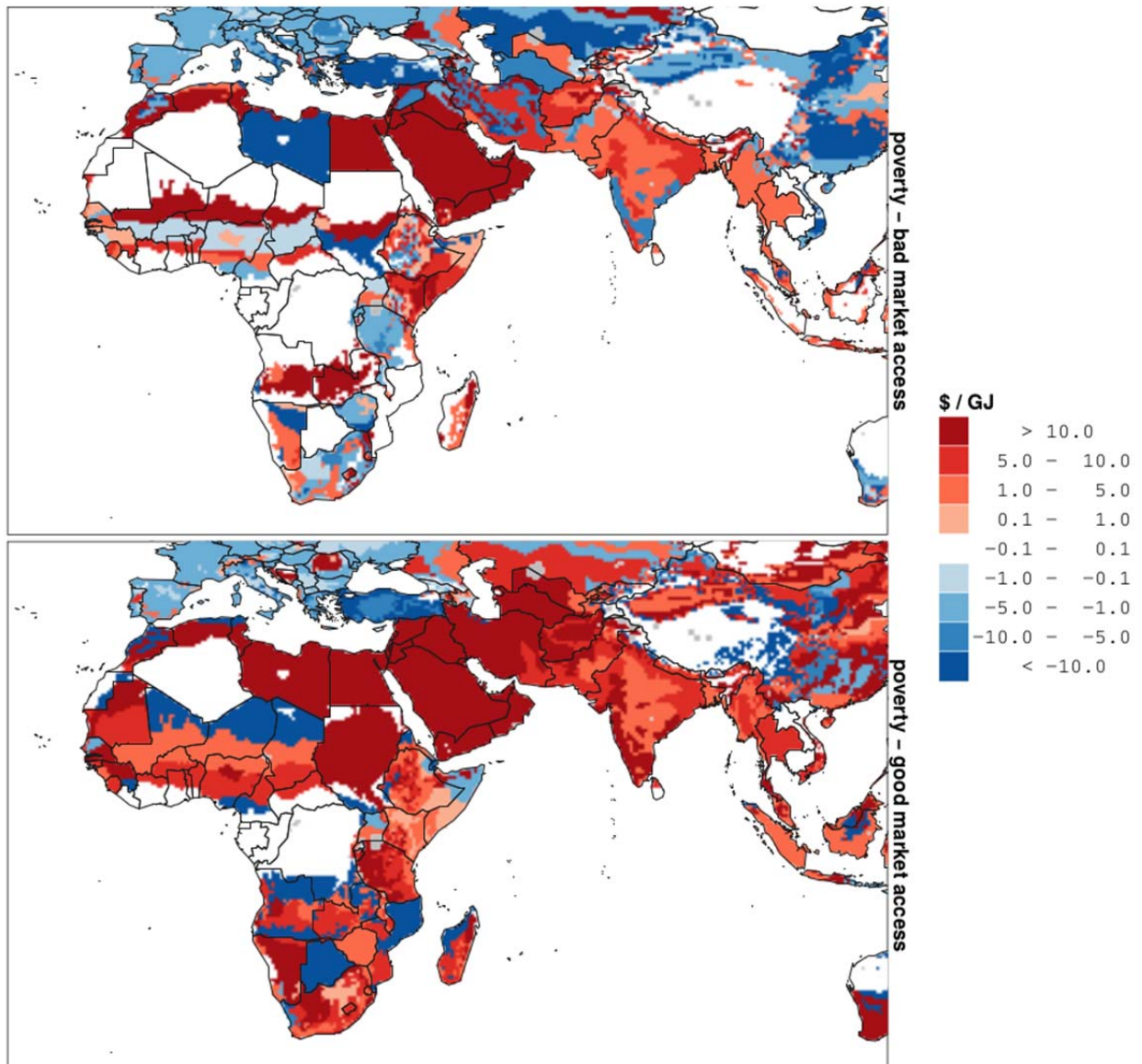


Figure 29: Cellular difference in Costs of Food in 2030 for RCP8.5 compared to a no climate change scenario (climate change - no climate change), for the poverty scenario and two market access scenarios. Positive values (red) indicate that Costs of Food increase, while negative values (blue) show that Costs of Food decrease.

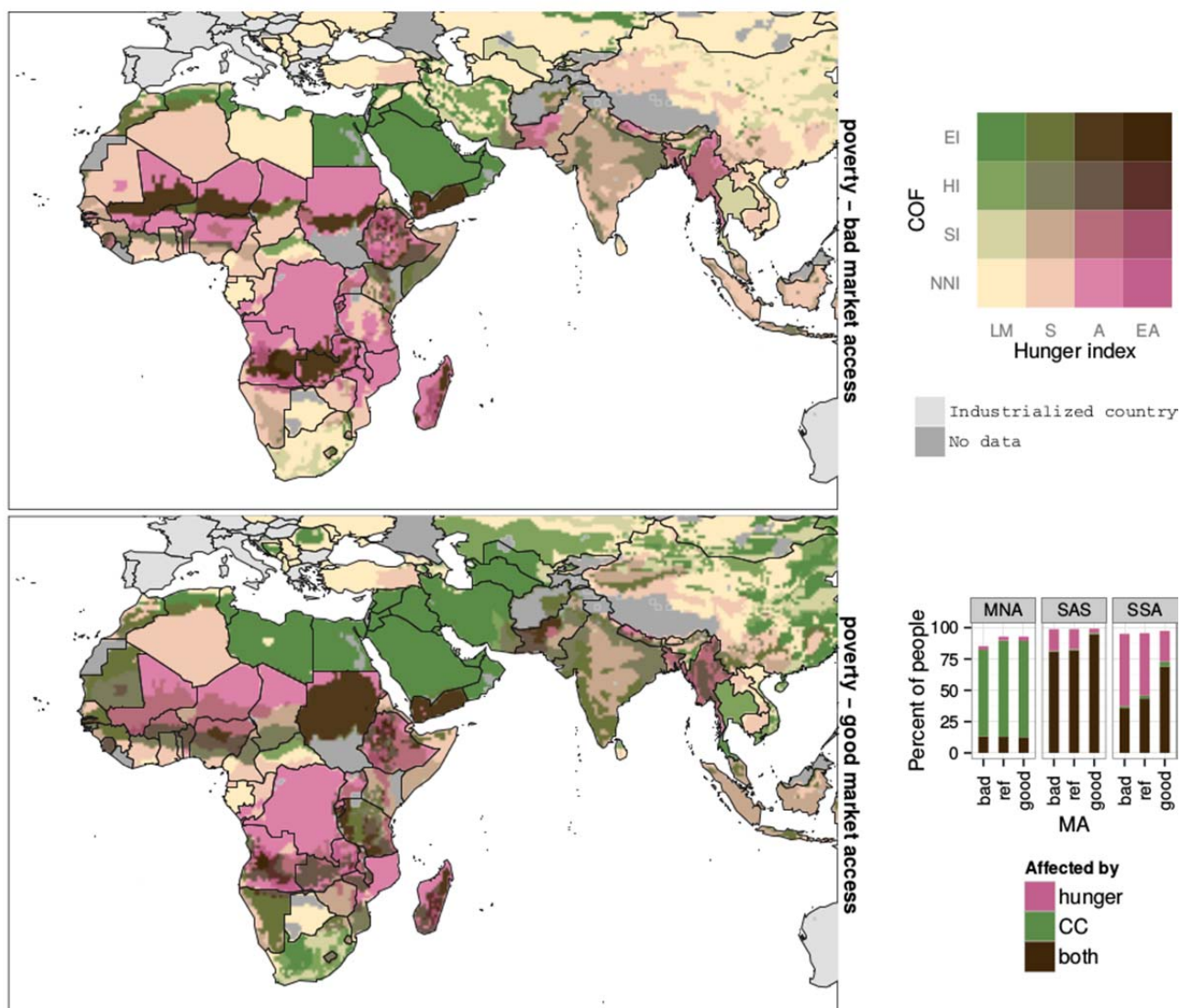


Figure 30: Cellular Agricultural Vulnerability Indicator based on the differences of Costs of Food between RCP8.5 and a no climate change scenario (climate change – no climate change), combined with the projected Vulnerability to Hunger Index for the year 2030, for the poverty scenario and two different market access scenarios (map). Number of people negatively affected by climate-induced increases in Costs of Food, exposure to hunger and both (barplot).

(Hunger levels: EA = extremely alarming, A = alarming, S = serious, LM = moderate and low, Climate change impact categories: EI = extremely high impact, HI = high impact, SI = strong impact, NNI = no negative impact; Region names: MNA = Middle East and North Africa, SAS = South Asia, SSA = Sub-Saharan Africa.)

6.9 The impact of climate change on production and yields in 2080 compared to 2030 for the three focus regions

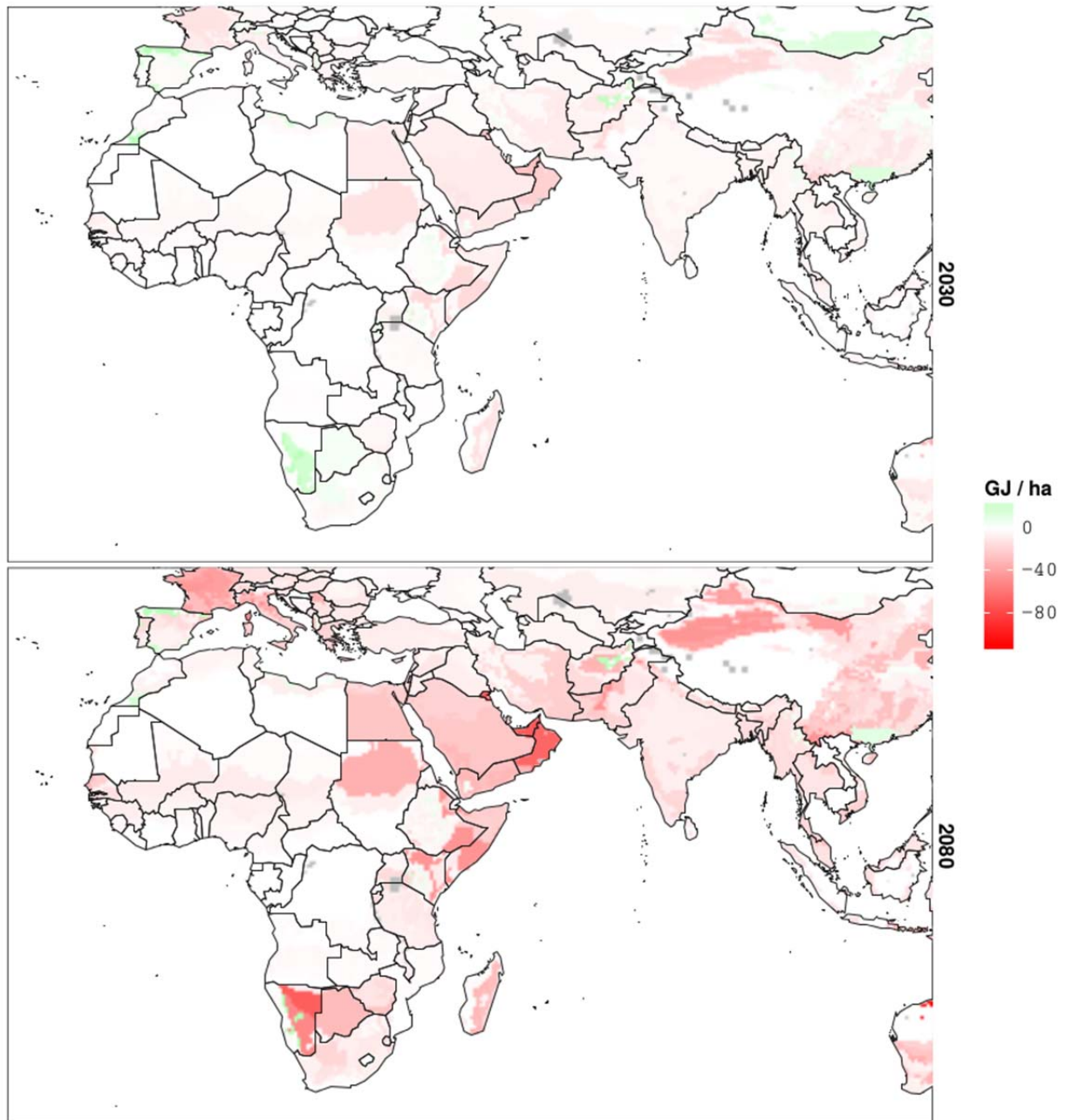


Figure 31: Cellular average difference in biophysical yields for 2030 and 2080 for RCP8.5 compared to a no climate change scenario (climate change - no climate change). Positive values (green) indicate that yields increase, while negative values (red) show that yields decrease.

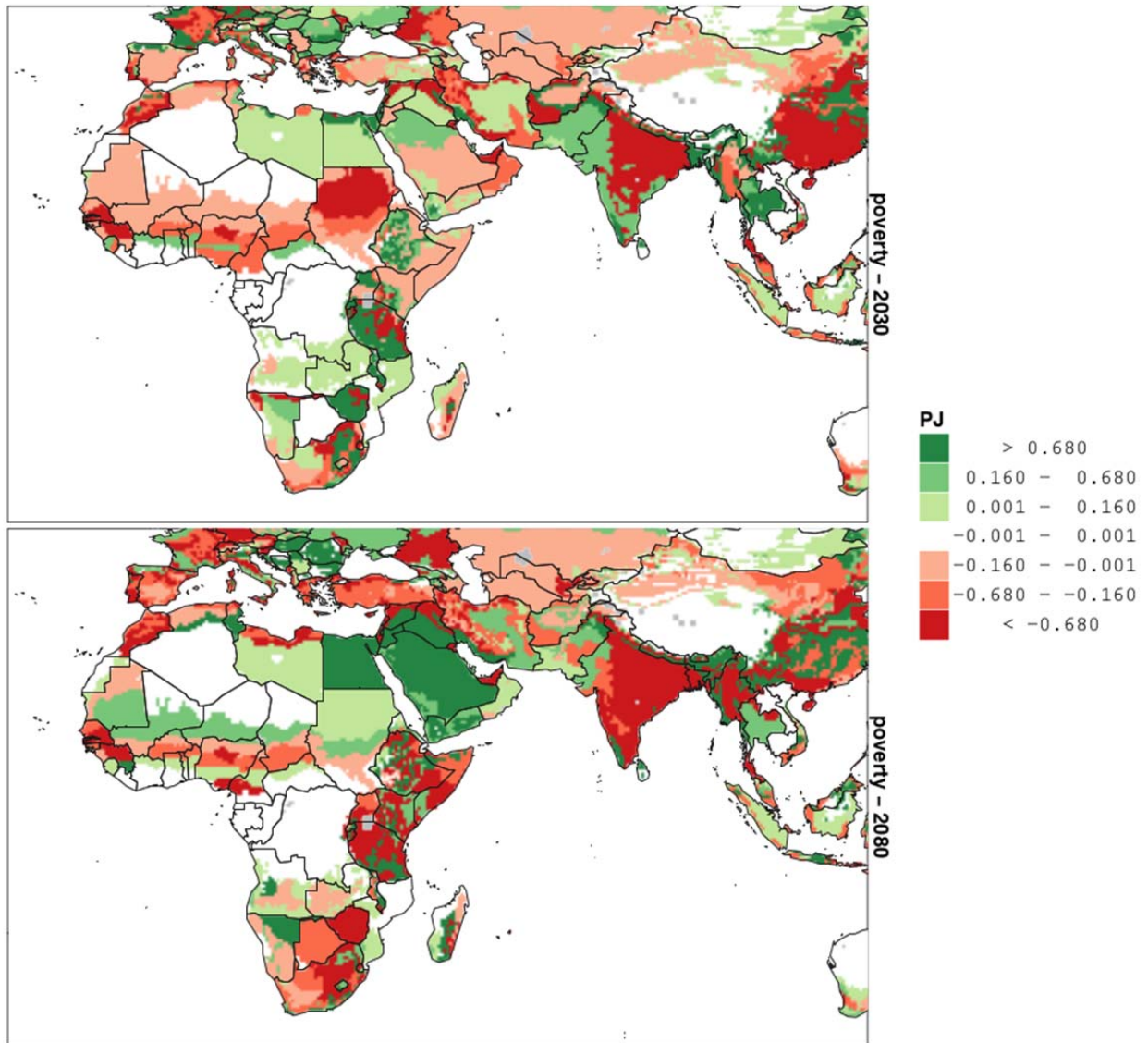


Figure 32: Cellular average difference in production of food crops for 2030 and 2080 for RCP8.5 compared to a no climate change scenario (climate change - no climate change), for the poverty scenario. Positive values (green) indicate that production increases, while negative values (red) show that production decreases. (Biophysical results are independent of socioeconomic settings.)

6.10 Global impacts of climate change on yields, water availability, production, Costs of Food and people exposed to hunger

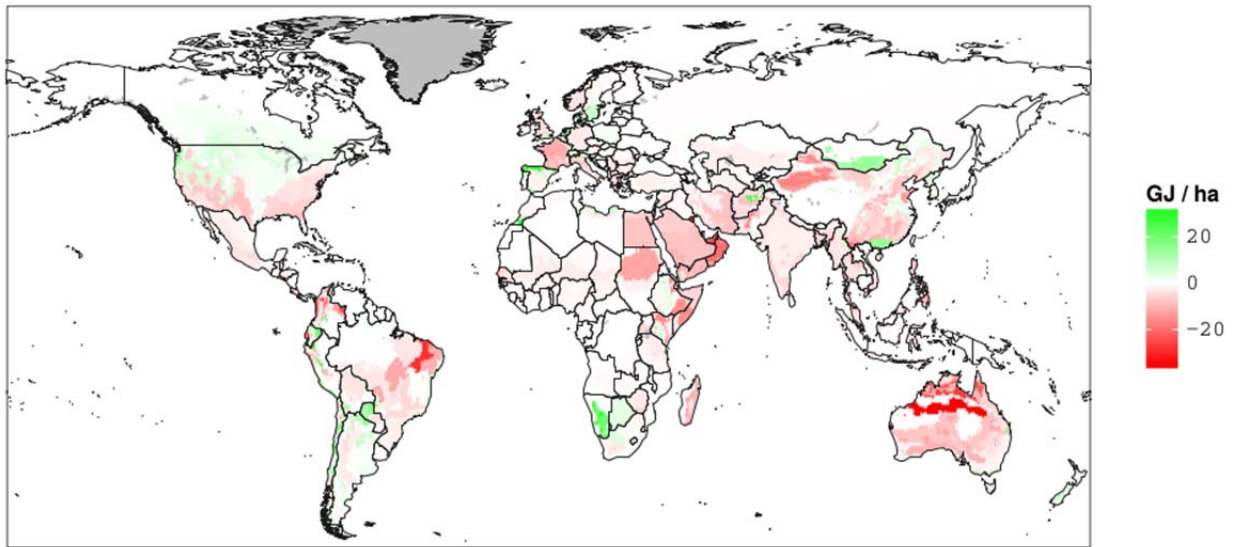


Figure 33: Cellular difference in biophysical yields for 2030 (global coverage) for RCP8.5 compared to a no climate change scenario (climate change - no climate change). Positive values (green) indicate that yields increase, while negative values (red) show that yields decrease.

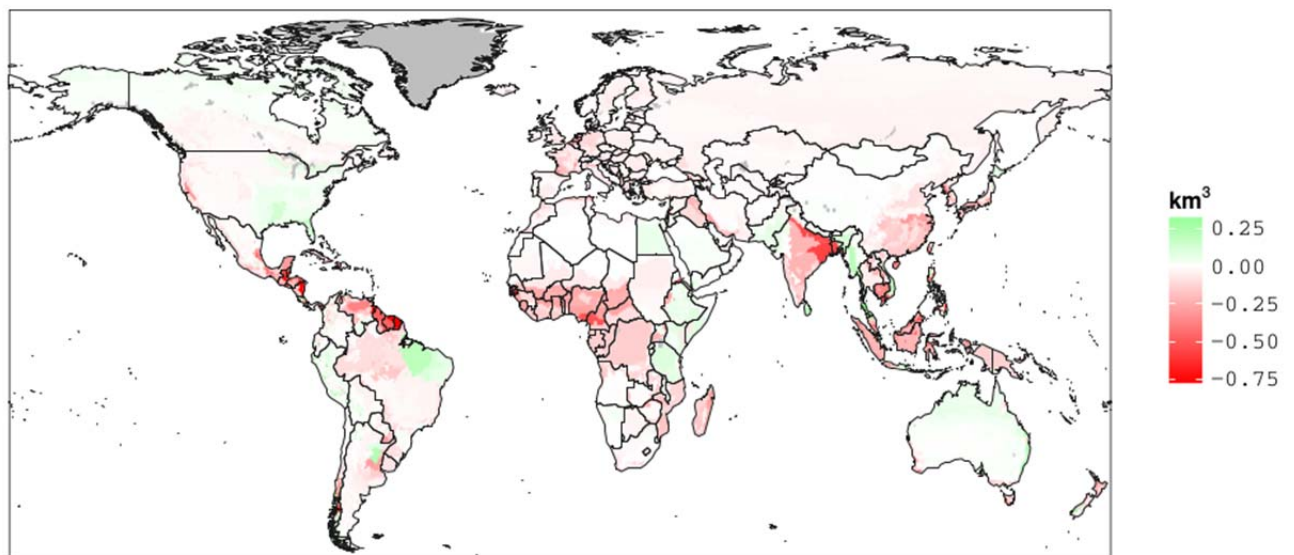


Figure 34: Cellular difference in biophysical water availability for 2030 (global coverage) for RCP8.5 compared to a no climate change scenario (climate change - no climate change). Positive values (green) indicate that water availability increases, while negative values (red) show that water availability decreases. (Biophysical results are independent of socioeconomic settings.)

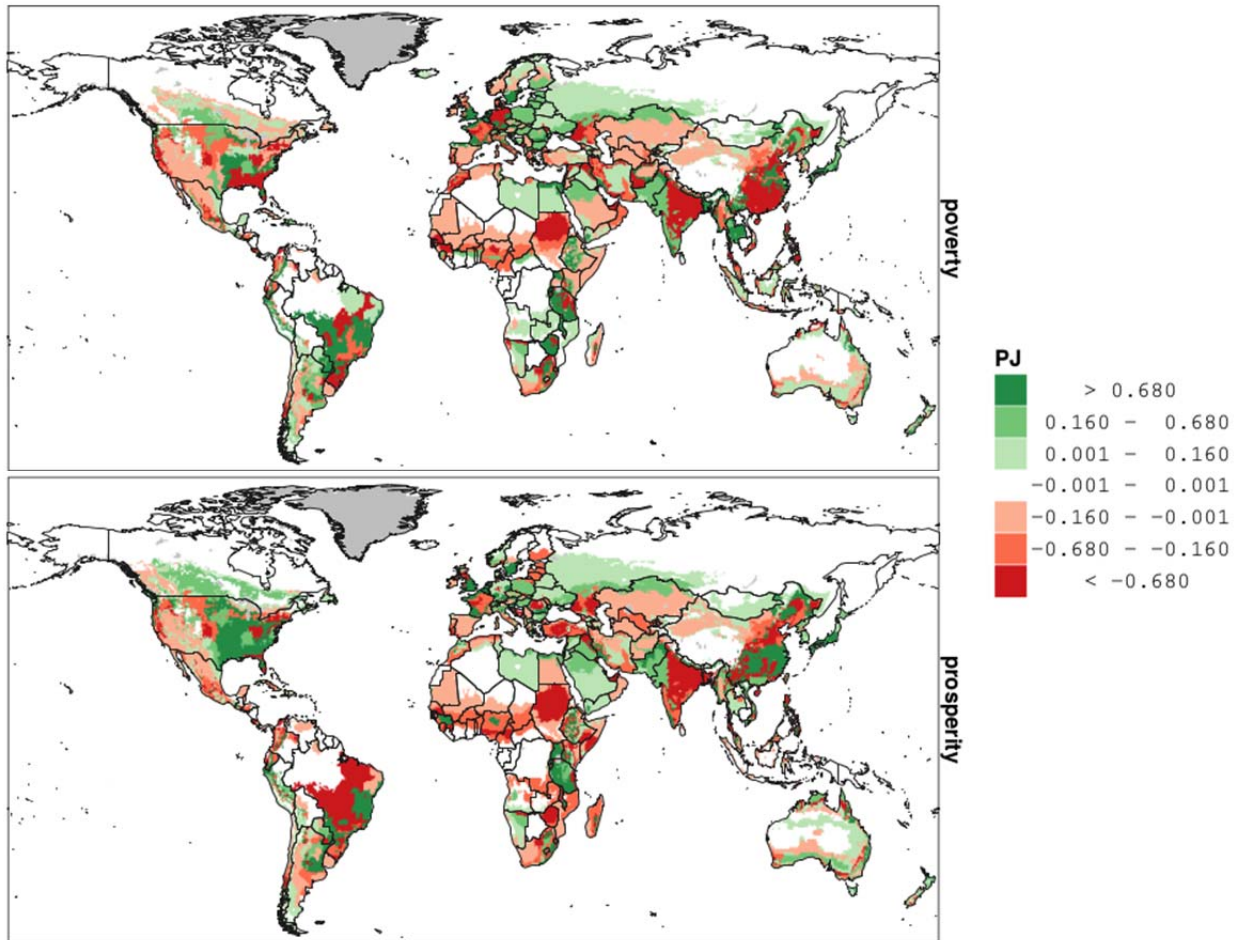


Figure 35: Cellular difference in production of food crops for 2030 (global coverage), for two socioeconomic scenarios, for RCP8.5 compared to a no climate change scenario (climate change - no climate change). Positive values (green) indicate that production increases, while negative values (red) show that production decreases.

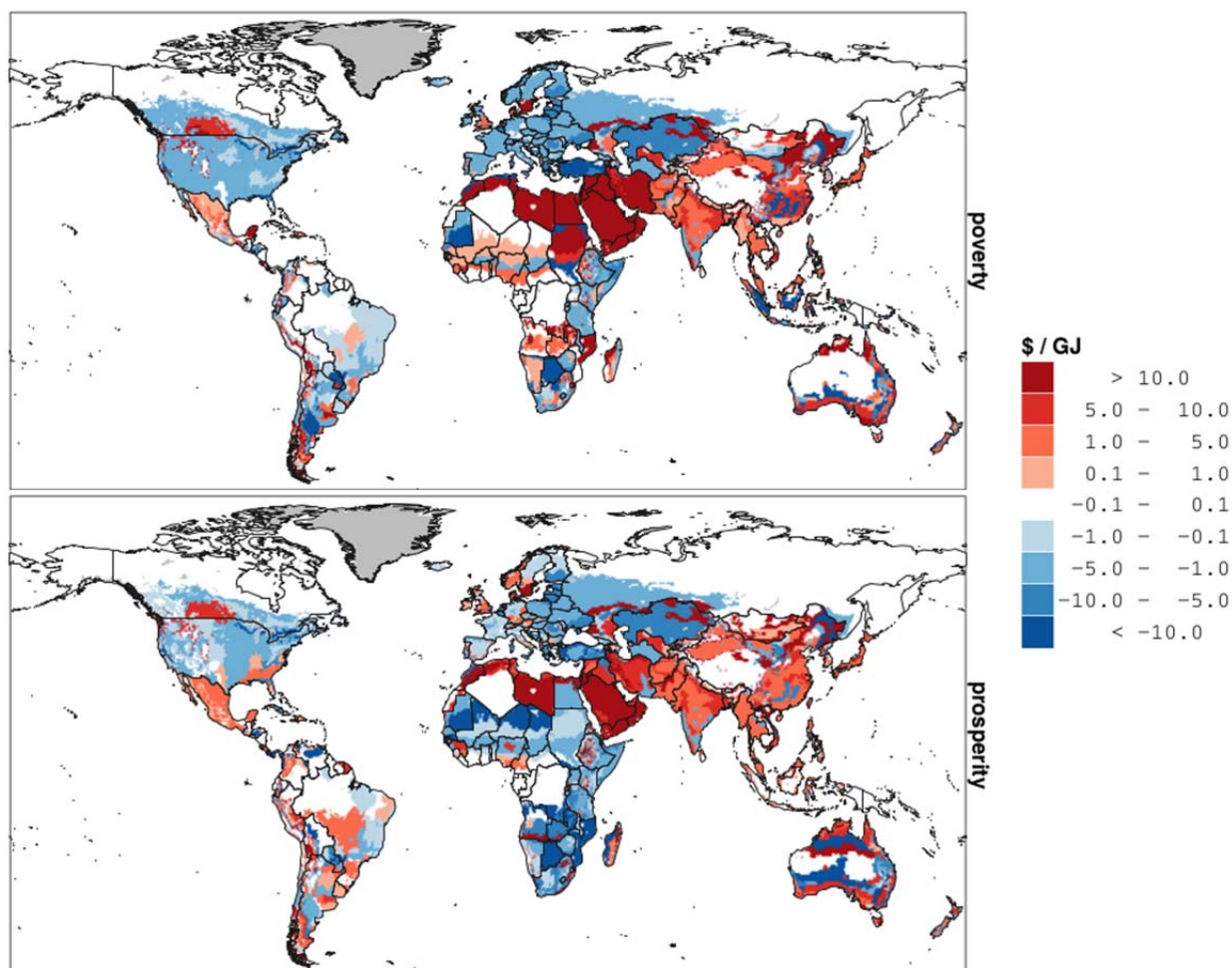


Figure 36: Cellular difference in Costs of Food in 2030 (global coverage) for RCP8.5 compared to a no climate change scenario (climate change - no climate change), for two socioeconomic scenarios. Positive values (red) indicate that Costs of Food increase, while negative values (blue) show that Costs of Food decrease.

Table 8: Global number of people (in million) affected by climate-induced increases in Costs of Food (RCP8.5 - no climate change) sorted by impact categories on Costs of Food (rows) and exposure to hunger for different Vulnerability to Hunger Index categories (columns) in 2030, for two socioeconomic scenarios.

	Poverty				Prosperity			
	Low and moderate	Strong	Alarming	Extremely alarming	Low and moderate	Strong	Alarming	Extremely alarming
No negative impact	1790	1009	413	46	2349	539	211	0
Serious impact	909	1266	460	33	1896	781	16	3
High impact	470	626	16	0	830	531	26	0
Extremely high impact	535	146	124	16	378	79	24	0

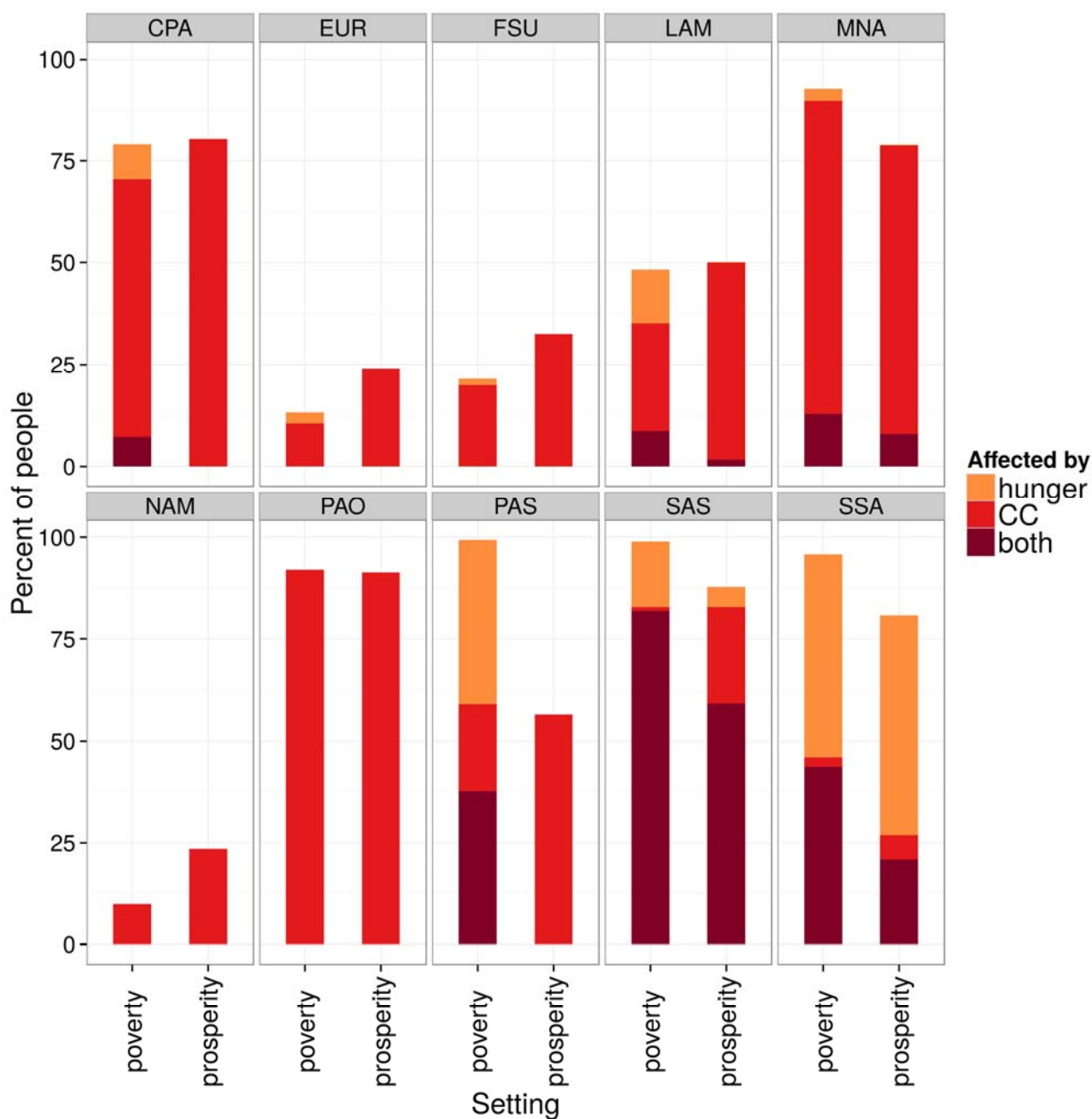


Figure 37: Percentage of regional people negatively affected by increases in Costs of Food caused by climate change (RCP8.5 – no climate change), exposed to hunger and both for the 10 world regions. Region names for the three focus regions (MNA, SAS, SSA) are based on the World Bank definition, the others on MAgPIE region names. (Region names: CPA = Centrally Planned Asia, EUR = Europe, FSU = Former Soviet Union, LAM = Latin America, MNA = Middle East and North Africa, NAM = North America, PAO = Pacific OECD, PAS = Pacific Asia, SAS=South Asia, SSA = Sub-Saharan Africa.)

6.11 Land and water shadow prices 2030 for 10 world regions

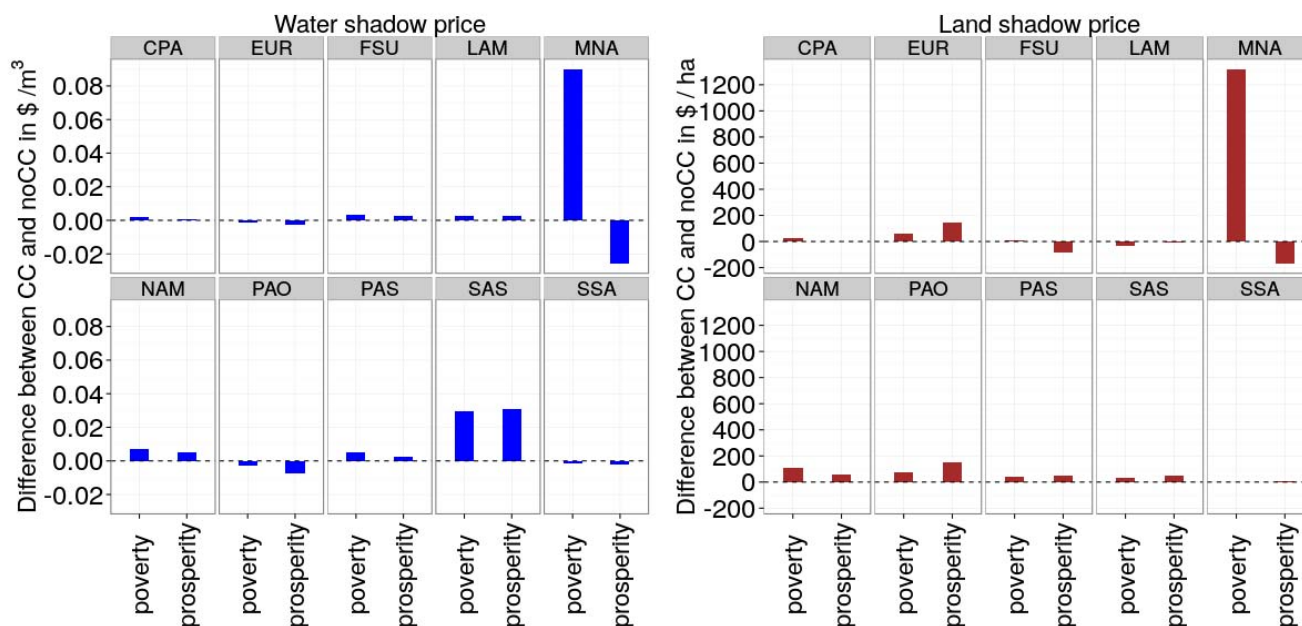


Figure 38: Regional absolute differences for land- and water shadow prices for two socioeconomic scenarios, for RCP8.5 compared to a no climate change scenario (climate change-no climate change) for the year 2030 for the ten world regions. Region names for the three focus regions (MNA, SAS, SSA) are based on the World Bank definition, the others on MAgPIE region names. (Region names: CPA = Centrally Planned Asia, EUR = Europe, FSU = Former Soviet Union, LAM = Latin America, MNA = Middle East and North Africa, NAM = North America, PAO = Pacific OECD, PAS = Pacific Asia, SAS = South Asia, SSA = Sub-Saharan Africa.)

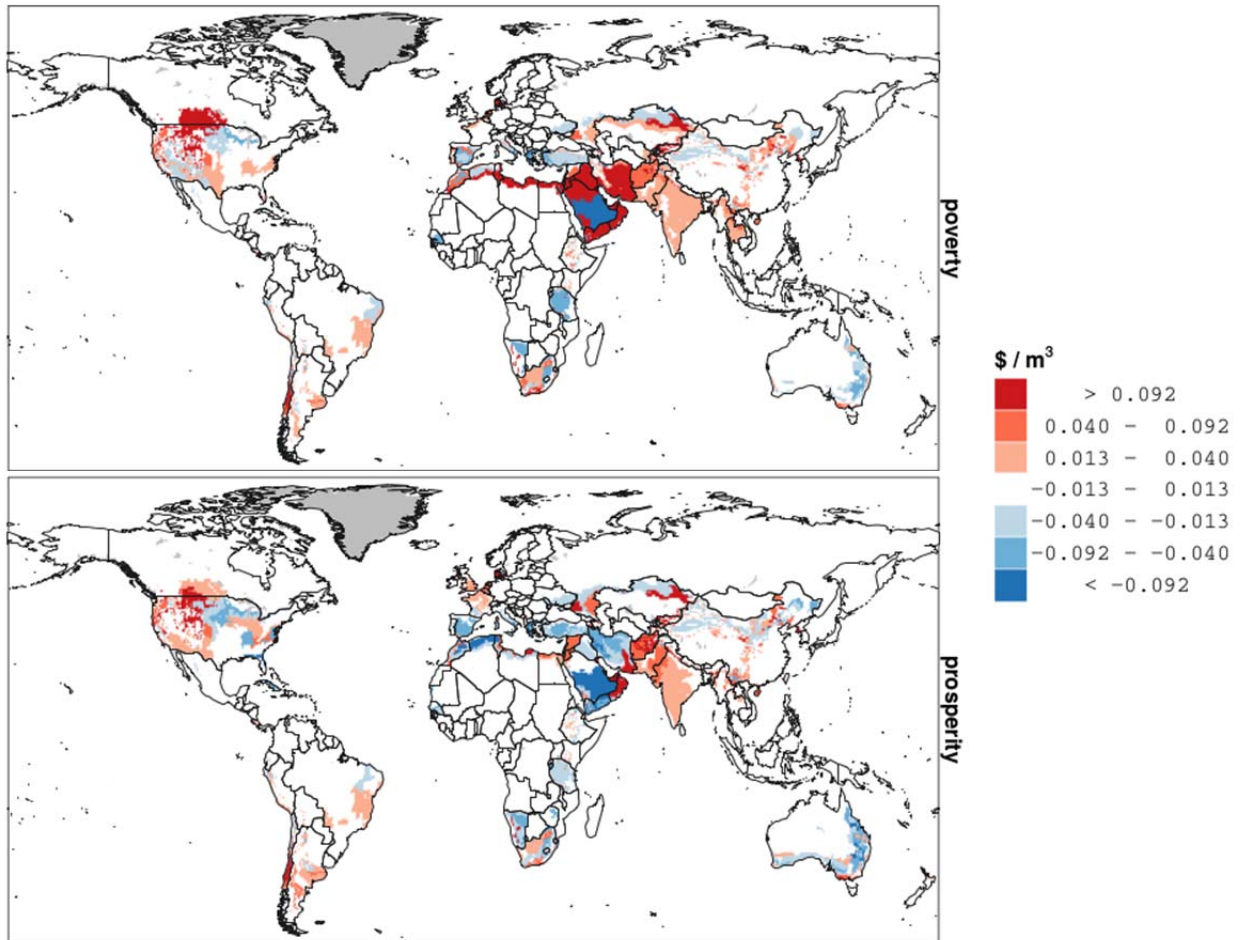


Figure 39: Cellular difference in water shadow prices for 2030 (global coverage), for two socioeconomic scenarios, for RCP8.5 compared to a no climate change scenario (climate change-no climate change). Positive values (red) indicate that the water shadow prices increase, while negative values (blue) show that the water shadow prices decrease.

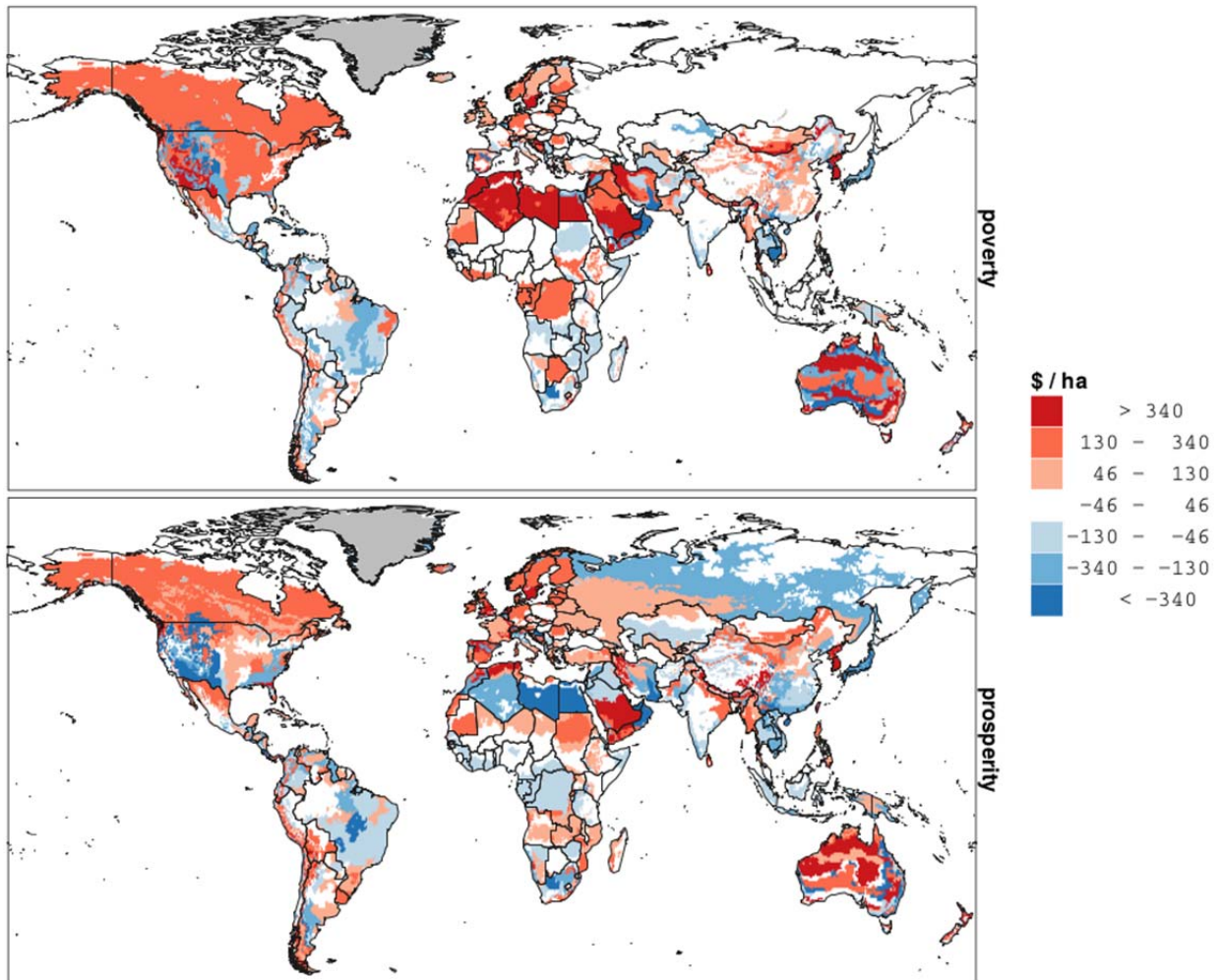


Figure 40: Cellular difference in land shadow prices for 2030 (global coverage), for two socioeconomic scenarios, for RCP8.5 compared to a no climate change scenario (climate change-no climate change). Positive values (red) indicate that the land shadow prices increase, while negative values (blue) show that land shadow prices decrease.

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