Climate change impacts on crop productivity in global semi-arid areas and selected semi-arid economies

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PRISE
Pathways to resilience in semi-arid economies

Research for climate–resilient futures

Climate change impacts on crop productivity in global semi-arid areas and selected semi-arid economies

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This report has been produced as part of a series of preliminary papers to guide the long-term research agenda of the Pathways to Resilience in Semi-arid Economies (PRISE) project. PRISE is a five-year, multi-country research project that generates new knowledge about how economic development in semi-arid regions can be made more equitable and resilient to climate change.

Front cover image:
Millet field after harvest, Sanmatenga Province, Burkina Faso

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Executive summary

This paper presents a comprehensive assessment of climate change impacts on crop productivity in semi-arid croplands in the world for the 2030s relative to the 2000s under a business-as- usual greenhouse gases (GHGs) emissions scenario (all results are shown for the emission rates associated with Radiative Concentration Pathway (RCP) 8.5).

Simulated changes in the extent of semi-arid areas and impacts on crop yield are presented. The geographical focus of this analysis is global, with a particular emphasis on six Pathways to Resilience in Semi-Arid Economies (PRISE) countries: Senegal, Burkina Faso, Kenya and Tanzania in Africa and Pakistan and Tajikistan in Central Asia. Results are shown with changes in climate (temperature, precipitation and radiation) from five different global climate models (GCMs) and crop yield impacts simulated by six different global gridded crop models (GGCMs) (an ensemble of 30 simulations). The results are sourced from a global climate impact assessment programme (Inter-Sectoral Impact Modelling Intercomparison Project (ISI-MIP)) and represent a state-of-the-art dataset of consistent model simulations, which reflect the key sources of uncertainty in climate impact assessment. The median (central value) of the ensemble and the median range are shown to represent the fairly high levels of uncertainty in crop impacts.

Main findings

Changes in the extent of semi-arid areas

Global changes

Semi-arid areas include hot (mean annual temperature ≥18ºC) and cold (mean annual temperature <18ºC) arid steppes. These cover 10% of the total land surface of the world circa the year 2000. Globally, cold semi-arid areas decrease slightly and hot semi-arid areas increase by the 2030s in the ensemble median. By the 2030s, global semi-arid areas decrease by 2%, 6.9% and 11.6% under three climate models but increase by 0.1% and 9.3% under two models. The share of semi-arid areas decreases by -2±4.8% in the median ensemble (see Table 1).

The location and extent of changes in the area of semi-arid conditions vary across climate simulations. For wetter climate scenarios, some parts of global semi-arid areas become tropical savannah. In contrast, under dryer scenarios, some parts of temperate and/or tropical areas become semi-arid and some parts of global semi-arid areas, in turn, become desert.

PRISE countries

For the PRISE countries, the results show a general decrease in semi-arid areas for all countries except Tanzania (30±57.8%) and Senegal (0.1±5.6%). Burkina Faso displays the largest decrease in semi-arid areas (-17.7±20.6%), followed by Kenya (-2.7±17.7%) (see Table).

Senegal: Three climate models project a drier climate, resulting in nearly half of current semi-arid areas in Senegal becoming desert. Two climate models simulate a wetter climate, resulting in nearly 62% of current desert areas becoming semi-arid; in one case, 25% of the current semi-arid areas transition to tropical savannah.

Burkina Faso: 8-73% of current semi-arid areas become tropical savannah according to four GCMs predicting wetter conditions; yet 15% of current tropical savannah areas turn semi-arid according to one climate scenario predicting dryer conditions.

Kenya: A large share of current semi-arid areas (between 21% and 45%) could become wetter – that is, tropical savannah – according to four GCMs but one GCM indicates a dryer climate with 16% of current tropical savannah to become hot-semi-arid.

Tanzania: Temperature increases lead to 35-69% of temperate climatic zone in the highland becoming tropical savannah. Four GCMs predict wetter scenarios leading to a small decrease in current semi-arid areas for three of them (to become tropical savannah) and total conversion of semi-arid areas into tropical savannah according to the fourth GCM. One GCM, however, predicts a slightly dryer scenario, leading to 5% of current tropical savannah becoming semi-arid.

Pakistan: The climate becomes hotter. Two GCMs suggest a dryer climate, with 32-55% of semi-arid areas to become desert and 10-15% of current temperate zones to become semi-arid. Two other GCMs predict a slightly wetter climate, with desert shifting to semi-arid and semi-arid shifting to temperate climate. Finally, another GCM also predicts 13% of current semi-arid areas will become temperate. Yet 18% of current temperate areas could also become semi-arid.

Tajikistan: A large share of current temperate zones could become semi-arid according to four GCMs (between 25% and 67%). A fifth GCM even predicts that 18% of current semi-arid areas could dry out and become desert. Cold climatic regions decrease under all GCM scenarios up to 30.2%.

Table 1: Summary of results on climate impacts on the extent of semi-arid areas (relative change in semi-arid areas given in %) and simulated crop yield (relative change in yield given in %) by 2030

	Semi-Arid Areas	CC (w CO_2)		CC (w/o CO_2)	
		Rainfed Yield	Irrigated Yield	Rainfed Yield	Irrigated Yield
Global	-2±4..8	4.7±9.6	-1.1±5	-4.5±7.3	-7.1±9.6
Senegal	0.1±5.6	-7.5±16.7	na	-8.5±9.9	na
Burkina-Faso	-17.7±20.6	1.7±9.9	na	-3.9±4.3	na
Kenya	-2.7±17.7	3.6±10.8	na	-1.9±12.4	na
Tanzania	30±57.8	-1.4±10.1	na	-4.4±10	na
Pakistan	-1.7±83.9	3.6±21.5	-0.7±8.6	-9.6±11.1	-9.7±11.2
Tajikistan	-0.3±18.3	1.4±12.5	3±9.6	-5.2±13.2	-5.3±7.3

Note: Changes in yield are shown for rainfed and irrigated conditions both including and excluding physiological effects of CO2 on crops. Irrigated agriculture is quasi non-existent in the African countries (<3% of total crop harvested areas).

Source: author

Changes in crop yield

Crop simulations are available for rainfed and irrigated conditions, according to present-day rainfed and irrigated areas. Here, irrigation requirements in the future are assumed to be fully satisfied (this will not necessarily be the case). Results are also presented with and without the effects of CO_2 fertilisation, which tends to have a beneficial effect on crop yield (depending on crop type and other factors).

Wheat is the predominant crop grown in semi-arid regions, occupying 29% of total crop harvested areas, followed by millet (17%) and sorghum (13%). All of millet and sorghum production are cultivated on rainfed lands, whereas 42% of wheat harvested area is irrigated. Other important crops grown in the semi-arid climate include cotton, accounting for 9% of the total cropland, as well as maize and groundnut (each covering 8% of total cropland in semi-arid areas).

Global changes

Median yield across all crops in the simulation ensemble (based on the current semi-arid areas) increases by 4.7±9.6% under rainfed conditions when including the effects of both changes in climate and elevated CO_2 concentrations. Median yield decreases by 1.1±5% under irrigated conditions, which accounts for 19% of total semi-arid croplands. By the 2030s, models predict a generally wetter climate that mostly benefits rainfed crop production since irrigated crops already have sufficient water. Both rainfed and irrigated crops are vulnerable to extreme temperature stress. In the case of rainfed conditions, results indicate effects of reductions in water stress from a wetter climate are greater than those of increases in temperature stress. Irrigated yield (which comprise primarily wheat, rice and maize grown in Central Asia) show overall decreases as a result of temperature stress.

When excluding the effects of elevated CO_2 concentrations, median yield decreases by 4.5±7.3% and 7.1±3.8% under rainfed and irrigated conditions, respectively.

Results synthesised here confirm that overall crop yield in semi-arid areas are negatively impacted by climate change, especially when excluding the possibility of a strong CO_2 yield enhancement. Both temperature and water stresses cause yield reductions. The overall spread in yield changes is important, especially when simulations include effects of changes in temperature, precipitation and CO_2.

PRISE countries

For the PRISE countries, the results show a median decrease in rainfed crop yield for Senegal (-7.5±16.7%) and Tanzania (-1.4±10.1%) and a median increase in crop yield for Burkina Faso (1.7±9.9%), Kenya (3.6±10.8%), Pakistan (3.6.1±21.5%) and Tajikistan (1.4±12.5%). Irrigated yield in Pakistan decrease slightly (-0.7±8.6%), while those of Tajikistan increase (3±9.6%). However, impacts on specific crops vary largely, as some crops are more or less tolerant to water and temperatures stresses than others.

The range in simulated crop yield is much more important than the range in simulated semi-arid areas. Results also include climate impacts on crop yield without the effects of elevated CO_2 on crop photosynthesis and water demand. In this case, the range of uncertainties is reduced but both rainfed and irrigated yield decrease systematically in all cases (see Table 1).

Senegal: Crop yield of the top-four most produced crops (groundnut, millet, sorghum and maize) decrease by the 2030s, even when including positive effects of CO_2.

Burkina Faso: Crop yield of millet and sorghum increase slightly when including CO_2 but yield of groundnut and maize decrease.

Kenya: Maize yield increases when including CO_2 whereas yield of all other important crops (such as beans, sorghum, wheat and millet) decrease.

Tanzania: Yield of maize and cotton decrease; yields of millet and wheat increase.

Pakistan: Yield of most rainfed crops increase (especially for cotton, rice and sugarcane). Changes in yield of both irrigated and rainfed wheat remain close to zero in the ensemble median. Irrigated maize is found to decrease notably even when accounting for CO_2 effects.

Tajikistan: Yield of irrigated rice and maize decrease, as does that of rainfed cotton. Yield of wheat increase slightly when including CO_2 effects but decrease otherwise as does peas and millet.

Key sources of uncertainty

The range of impacts in crop yield result from the combined effects of contrasting spatial patterns of change in temperature, precipitation and radiation as simulated by the climate models and the different sensitivities of the crop models to each of these factors and the direct effects of increasing atmospheric CO_2 (taken from the RCP 8.5 scenario).

In all cases, the range of impacts is larger than the median change, and there are major differences in the results with and without CO_2 effects.

The impact simulations do not take into account changes in the availability of water for irrigation, and assume irrigation water is available for fully counteracting water stress on irrigated crops. However, optimum irrigation may not be realised in the fields, especially as climate change alters water resources in the future.

Implications for PRISE and PRISE countries

The median changes in crop yield are the central values from an ensemble of (in most cases) 30 simulations – each outcome is equally valid and therefore in terms of planning for impacts the full range should be considered.

To fully assess the practical and policy significance of simulated impacts requires situating the changes in the context of current and future (2030) vulnerability in agriculture-based livelihoods. The results presented here provide the basis for PRISE research to couple a comprehensive assessment of crop biophysical impacts with stakeholder-led interpretations of their significance for planning and adaptation.

Large changes in yield or extent of semi-arid land (i.e. more negative than -5%) by 2030 could have significant consequences for agricultural production and land use. Examples of strongly negative impacts include irrigated maize in Pakistan (-11.4±14.8%); rainfed cotton in Tajikistan (-11.4±14.8%) and Kenya (-11.4±14.8%); and rainfed maize in Senegal (-5.4±14.9%) and Tanzania (-3.2±10.7%). If the positive effects of CO_2 fertilisation are fully realised (note high uncertainty about the magnitude of the CO_2 effect), then many crops will produce higher yield, which, other things being equal, will increase agricultural production. However, this beneficial effect should be considered with extra caution as observations suggest a possible decline in the nutritional quality of crops grown under elevated CO_2.

Results presented for the 2050s and 2080s (see Appendix) show more significant negative effects occur as extreme temperature impacts begin to offset the beneficial effects of CO_2 fertilisation.

1. Introduction

Agricultural production in semi-arid regions is often low and subject to climate-related uncertainty and shocks. While several global crop-modelling studies have reported on potential impacts of climate change to date, none has focused on semi-arid systems (Porter et al., 2014). The existing literature on semi-arid systems consists of many case studies (Challinor et al., 2007; Hijioka et al., 2014; Niang et al., 2014), which are difficult to compare owing to differences in spatial scale, crop types and crop models; treatment of key factors such as carbon dioxide (CO_2) fertilisation; and climate change scenarios. Furthermore, country-level climate impact studies aggregate across production systems and preclude analysis of impacts and sensitivities in specific systems such as semi-arid regions. Although agricultural production in absolute terms may be low, its economic and social importance in many semi-arid regions is particularly high, for example through its high contribution to employment, sub-national economic activity and food security for subsistence producers. Agriculture is still seen as a key route to economic development, and agricultural development plans need to be climate-compatible (Diao et al., 2010).

This working paper addresses key knowledge gaps on the sources of uncertainty and key sensitivities in crop production under climate change conditions in the world's semi-arid regions. Changes in global semi-arid areas in response to future climate change and corresponding crop yield are synthesised from a new ensemble of simulation results produced by the Inter-Sectoral Impact Modelling Intercomparison Project (ISI-MIP).[1]

The analysis presented here intends to examine potential impacts of climate change and increased climate variability on agricultural productivity in semi-arid areas and to address the Pathways to Resilience in Semi-Arid Economies (PRISE) inception phase objective to assess drivers of change and vulnerability in semi-arid lands for the period of the 2030s. The use of the ISI-MIP fast-track archive enables a comprehensive characterisation of uncertainty in projected impacts related to different climate change scenarios and crop yield simulations using different crop models.

The outputs provide a robust physical science basis to support adaptation decision-making in the agriculture sector in PRISE countries.

Section 2 presents the ISI-MIP data archive. Section 3 offers an overview of the results for global semi-arid areas, and Section 4 a more detailed summary of the results for the six PRISE countries. Section 5 discusses uncertainties and other limitations in this analysis, before Section 6 concludes.

[1] www.isi-mip.org

Climate change in Kenya, Samburu County.

Africa Progress Panel

2. The ISI-MIP data archive

ISI-MIP was launched to integrate climate impact assessments across multiple sectors. The ISI-MIP fast-track exercise, which took place between January 2012 and January 2013, consisted in the integration of climate impact models representing several sectors among water, agriculture, ecosystem, health, infrastructure and the economy at the global scale (Warszawski et al., 2014). The ISI-MIP data archive for the agriculture sector includes global gridded data of agricultural productivity, growing season evapotranspiration and other crop growth-relevant outputs produced by an ensemble of six global gridded crop models (GGCMs) simulating more than 15 crops (Rosenzweig et al., 2014)[2] driven by downscaled climate data from five general circulation models (GCMs) of the Coupled Model Intercomparison Project Phase 5 (CMIP5) run under four radiative concentration pathways (RCPs) of greenhouse gases (GHGs) emissions scenarios for the 21st century (Table 2; Hempel et al., 2013).

Here, this study focuses on 13 crops including maize, rice, wheat and soybean for the full ensemble of GGCMs, as well as millet, cassava, sugarcane, sunflower, groundnut, beans, cotton, sorghum and peas for a subset of two GGCMs. Results take into account effects of elevated atmospheric CO_2 concentrations under a business-as-usual GHGs emissions scenario (i.e. RCP 8.5) and differences between irrigated – assuming full irrigation – and rainfed cropping systems (Deryng, 2014; Rosenzweig et al., 2014). Crop-specific irrigated and rainfed areas are defined according to global maps of irrigated and rainfed crop areas around the year 2000 (Portmann et al., 2009). With respect to semi-arid areas, most crops presented in this report are grown under rainfed conditions, except for wheat and rice in Central Asia (see Table A2).

This analysis focuses on two time periods: circa the year 2000 for the baseline and circa the year 2030. Results from the ISI-MIP archive are provided yearly from 1971 to 2099. Here, we used 10-year averages, centred on both 2000 and 2030, to estimate changes in climatic and crop yield outputs from the GCMs and GGCMs, respectively. Results are presented for the median change across five GCMs and six GGCMs (two for certain crops), totalising 30 (10) simulations. The range is presented by the median absolute deviation (MAD), a robust measure of the scatter. The Appendix contains results for the 2050s and the 2080s based on the same approach.

[2] Please see the Supplemental Information of Rosenzweig et al. (2014) for a full technical description of the GGCMs (i.e. reference, simulated processes, calibration and validation methods).

Table 2: List of GCMs and GGCMs from the ISI-MIP archive, as well as simulated crops included in this study

GCM	
HadGEM2-ES	
IPSL-CM5A-LR	
MIROC-ESM-CHEM	
GFDL-ESM2M	
NorESM1-M	
GGCM	**CROP**
EPIC	Maize, Wheat, Soybean, Rice, Millet, Sorghum, Sugarcane, Beans, Cassava, Cotton, Sunflower, Groundnut
GEPIC	Maize, Wheat, Soybean, Rice
LPJmL	Maize, Wheat, Soybean, Rice, Millet, Cassava, Peas, Sunflower, Groundnut, Sugarcane
LPJ-GUESS	Maize, Wheat, Soybean, Rice
pDSSAT	Maize, Wheat, Soybean, Rice
PEGASUS	Maize, Wheat, Soybean

Source: Hempel et al., 2013

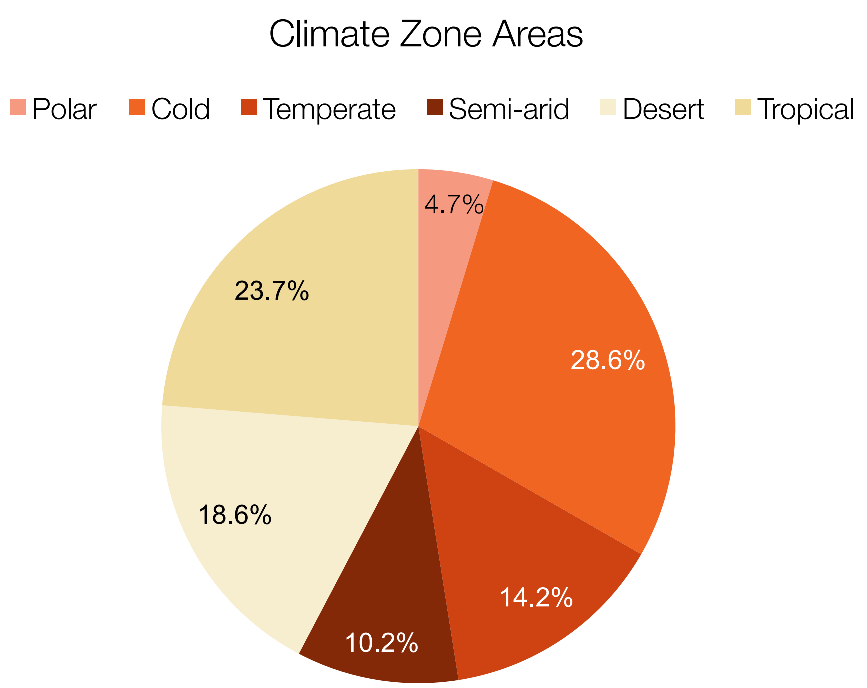
3. General findings: semi-arid areas

3.1 Semi-arid areas of the world

We use the Köppen-Geiger climatic classification rules (Peel et al., 2007) to identify semi-arid areas in the world (Table A1). Semi-arid areas include BSh and BSk climatic categories – that is, hot (mean annual temperature ≥18ºC) and cold (mean annual temperature <18ºC) arid steppes. These cover 10% of the total land surface of the world circa the year 2000 (Figure 1 and Table 3).

By the 2030s, global semi-arid areas decrease by 2%, 6.9% and 11.6% under the GFDL-ESM2M, HadGEM2-ES and IPSL-CM5A-LR climate-driven scenarios, respectively, but increase by 0.1% and 9.3% under NorESM1-M and MIROC-ESM-CHEM, respectively, under RCP 8.5. These changes include 3-5% of current temperate areas, 2-4% of current desert areas and 1-2% of current tropical areas becoming semi-arid and 9-19% of current semi-arid land becoming desert by the 2030s (Table 3).

Figure 1: Share of aggregated climatic zone areas in the world circa the year 2000 based on median % areas estimated across the five GCMs (%)



Source: author

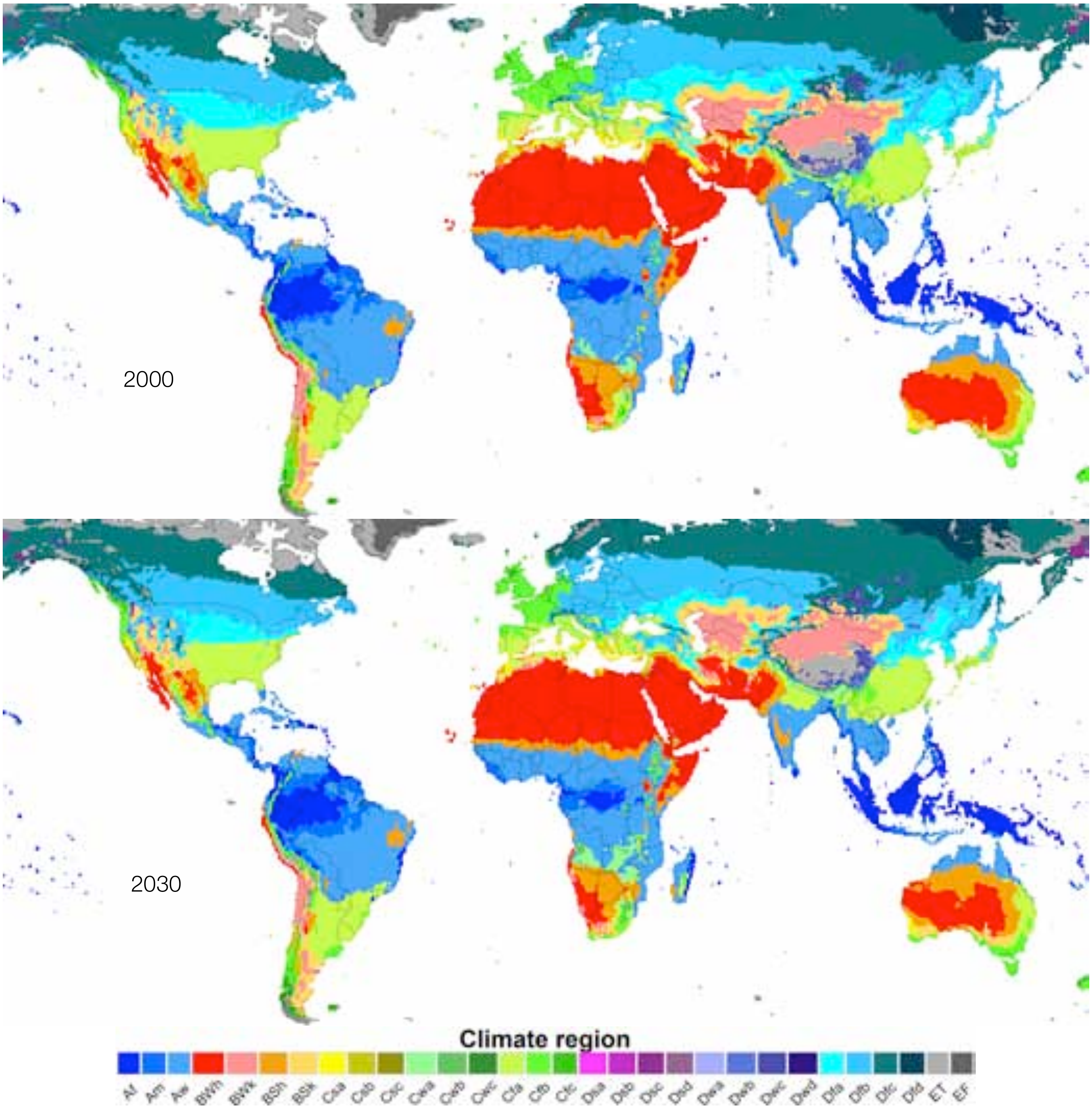
Table 3: Share of Köppen-Geiger climatic zone areas in the world in the year 2000 and 2030 (%)

Köppen-Geiger climatic zone	2000	2030
Tropical Rainforest	4.4±0.7	4.5±0.1
Tropical Monsoon	4±0.3	3.7±0.3
Tropical Savannah	15.4±0.8	17.6±1.0
Cold Desert	3.5±0.3	3.4±0.2
Hot Desert	15±0.2	15.7±0.1
Cold Semi-Arid	**3.9±0.1**	**3.6±0.1**
Hot Semi-Arid	**6.3±0.2**	**6.7±0.2**
Temperate – Dry/Hot Summer	0.5±0.1	0.7±0.1
Temperate – Dry/Warm Summer	0.3±0	0.3±0.0
Temperate – Dry/Cold Summer	<0.1	<0.1
Temperate – Dry Winter/Hot Summer	1.2±0.1	0.7±0.3
Temperate – Dry Winter/Warm Summer	0.5±0.1	0.3±0.1
Temperate – Dry Winter/Cold Summer	<0.1	<0.1
Temperate – w/o dry season/Hot Summer	8.4±0.3	8.6±0.1
Temperate – w/o dry season/Warm Summer	3.3±0.1	3±0.0
Temperate – w/o dry season/Cold Summer	0.1±0	0.1±0.0
Cold – Dry/Hot Summer	<0.1	0.1±0.0
Cold – Dry/Warm Summer	0.1±0	0.1±0.0
Cold – Dry/Cold Summer	0.4±0.2	0.6±0.3
Cold – Dry Winter/Hot Summer	0.1±0.1	<0.1
Cold – Dry Winter/Warm Summer	0.3±0.1	0.3±0.0
Cold – Dry Winter/Cold Summer	0.7±0.1	0.8±0.2
Cold – w/o dry season/Hot Summer	3.4±0.3	5.3±0.8
Cold – w/o dry season/Warm Summer	10.3±0.3	10.3±0.5
Cold – w/o dry season/Cold Summer	12.1±0.3	10.5±0.5
Cold – w/o dry season/Very Cold Summer	1.1±0.3	0.9±0.1
Polar Tundra	4.6±0.2	2.9±0.6
Polar Frost	<0.1	<0.1

Note: Values correspond to the median in the GCM ensemble; the range is the median absolute deviation from the median.

Source: author

Figure 2: Maps of Köppen-Geiger climate region in the world in the year 2000 (top) and 2030 (bottom)



Note: The climate category in each pixel corresponds to the majority among the five GCMs. Similar maps are included for the 2050s and 2080s in the Appendix. See Table A1 for a description of the climate regions. Bsh (orange) and Bsk (light-orange) correspond to hot and cold semi-arid climate regions, respectively.

Source: author

3.2 Change in yield in current semi-arid areas – implications for production

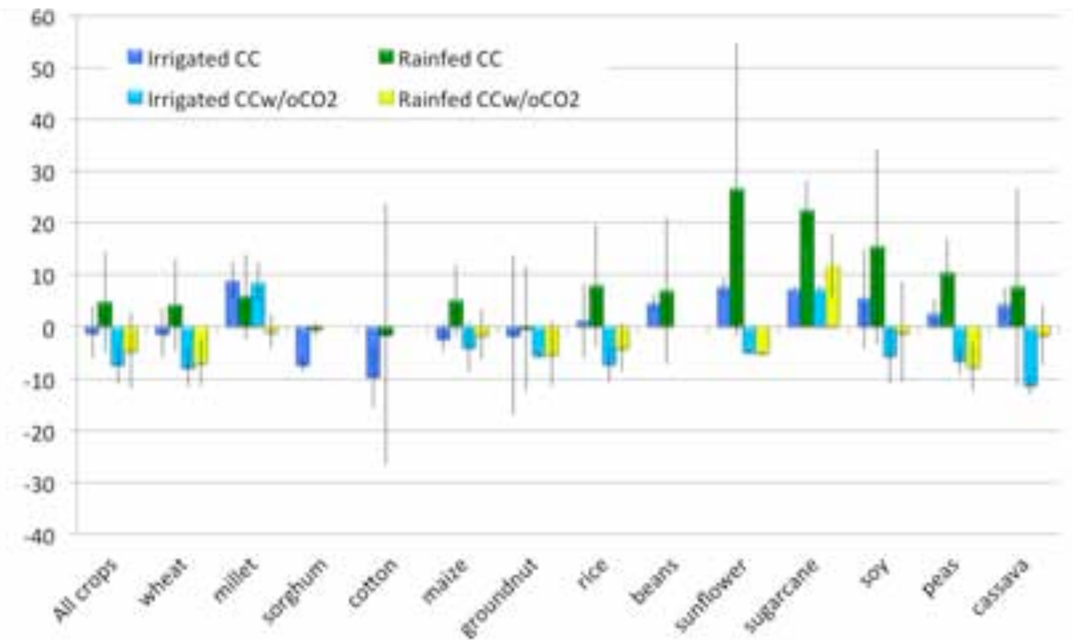
Wheat is currently the predominant crop grown in semi-arid regions according to observed crop harvest areas for the year 2000 (Monfreda et al., 2008), occupying 29% of total crop harvested areas. It is followed by millet (17%) and sorghum (13%). All of millet and sorghum production is cultivated on rainfed lands, whereas 42% of wheat harvested area is irrigated. Other important crops grown in the semi-arid climate include cotton, accounting for 9% of total cropland, as well as maize and groundnut (each covering 8% of total cropland in semi-arid areas). Cotton and groundnut are mainly grown on rainfed land and 16% of maize harvested area is irrigated (Table A2).

When including effects of both changes in climate (i.e. temperature, precipitation and radiation) and elevated CO_2 concentrations (further labelled as the *CC* scenario), median[3] yield across all crops in the simulation ensemble (based on the current semi-arid areas) increases by 4.7±9.6% under rainfed conditions (Figure 3 and Table A2). Median yield decreases by 1.1±5% under irrigated conditions, which accounts for 19% of total semi-arid croplands. By the 2030s, models predict a generally wetter climate that mostly benefits rainfed crop production, since irrigated crops already have sufficient water. However, increased temperature stress in the 2030s presents a key threat to crop production in irrigated areas. When excluding the effects of elevated CO_2 concentrations ($CC_{w/oCO2}$), median yield decreases by 4.5±7.3% and 7.1±3.8% under rainfed and irrigated conditions, respectively. These results indicate that CO_2 plays a fundamental role in determining impacts on yield (Table 3).

Impacts on crop yield differ among crop types, not only because different crops are grown in different locations but also because they have different temperature and water requirements and respond differently to elevated CO_2. Under *CC*, rainfed yield increases by 4.2±8.7%, 5±6.8% and 7.9±11.6% for wheat, maize and rice, respectively. Irrigated yield decreases for wheat (-1.2±4.7%) and maize (-2.1±2.6%) and increases for rice (1.2±7.1%). Millet yield increases by 5.8±8.1% whereas sorghum yield decreases by 0.5±1.2%. Yet millet was simulated by only two GGCMs (under rainfed conditions as irrigation is quasi non existent for these crops), including LPJmL (one of the most responsive models to beneficial CO_2 effects) and EPIC (one of the most sensitive models to negative heat stress) (Deryng, 2014; Rosenzweig et al., 2014). Under $CC_{w/oCO2}$, millet yield decreases by 0.9±3.2%. EPIC did not provide $CC_{w/oCO2}$ for sorghum (Figure 3 and Table A2). Sorghum and cotton were simulated only by EPIC and exhibit a larger yield reduction than the other crops under *CC*. In all cases, the range is greater than the median.

[3] Weighted medians were used to estimate median change across all crops, taking into account the relative importance of each crop. The corresponding irrigated and rainfed areas were used for the weighting factor.

Figure 3: Global crop yield change (median in the model ensemble) in semi-arid areas by the 2030s (%)



Note: Crops are sorted by decreasing harvested areas from left to right (e.g. wheat has the largest harvested areas and cassava the smallest). The error bars correspond to the median absolute deviation from the median. Wheat, maize and soybean include 30 simulations (6GGCMsx5GCMs); rice includes 25 simulations (5GGCMsx5GCMs); millet, cassava, sugarcane, sunflower and groundnut include 10 simulations (2GGCMsx5GCMs); peas, sorghum, beans and cotton include 5 simulations (1 GGCMx5GCMs).

Source: author

Free trade agriculture farmers, Tajikistan.

4. Impacts in PRISE countries

The selected PRISE countries include Senegal and Burkina Faso in western Sub-Saharan Africa, Kenya and Tanzania on the eastern coast and Tajikistan and Pakistan in South-Central Asia. These countries are all classified as low-income economies except Pakistan and Senegal, which are considered lower-middle-income economies. In each of these countries, a majority of the population continues to live in rural areas and the agriculture sector contributes to a large share of their economy.

4.1 Senegal

Senegal is classified as a lower-middle-income economy. The agriculture sector contributes to 17% of its gross domestic product (GDP) and 57% of the 13.5 million inhabitants currently live in rural areas (World Bank, 2014). Located in Sub-Saharan Africa, on the west coast and with direct access to the Atlantic Ocean, Senegal is predominantly a hot and dry country: 43±6% of the total area is classified as hot semi-arid, 17±8% as hot desert and 34±8% as tropical savannah[4] (Table 4).

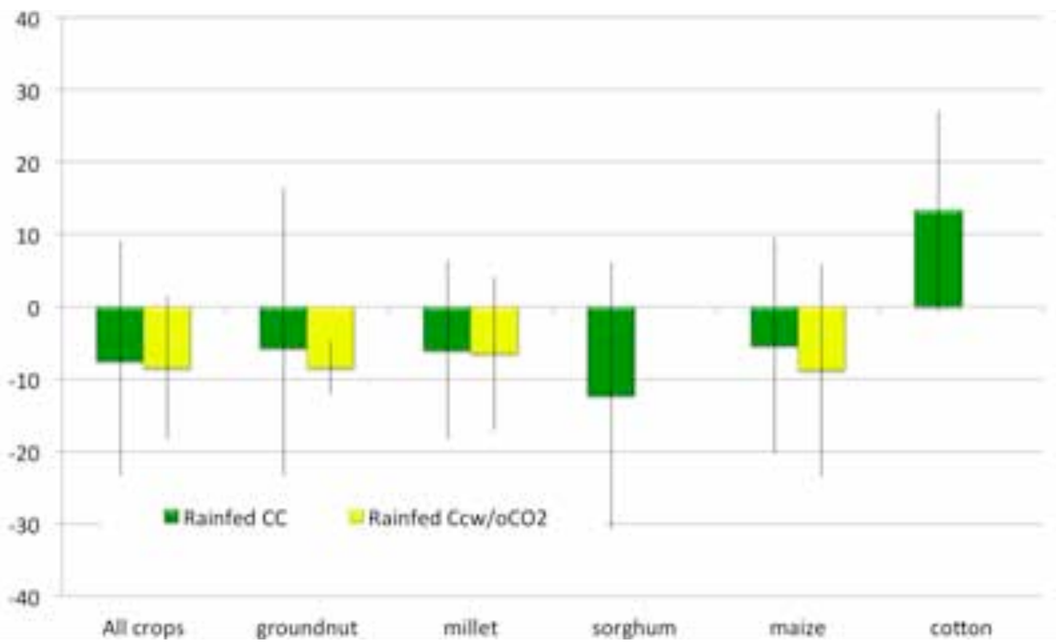
HadGEM2-ES, IPSL-CM5A-LR and GFDL-ESM2M predict a drier climate by the 2030s, resulting in nearly half of current semi-arid areas in Senegal becoming desert. On the opposite side, MIROC-ESM-CHEM and NorESM1-M simulate a wetter climate for Senegal, resulting in nearly 62% of current desert areas becoming semi-arid, and, in the case of MIROC-ESM-CHEM, 25% of the current semi-arid areas converting to tropical savannah (Table 4).

Cropland accounts for 46% of the country's total area. Groundnut, rice, millet sorghum and maize are important crops in terms of their overall production for national consumption. In addition, cotton is particularly important to Senegal's economy (FAO, 2014). A large share of millet and groundnut are cultivated in the semi-arid part of Senegal, accounting for 61% of the country's cropland. Cotton, rice, maize and sorghum are mostly grown in the tropical areas. Only 18% of rice and just about 4% of maize harvested areas are irrigated. All the other crops are grown under rainfed conditions (Table A2).

The overall impact on crop yield in the semi-arid areas is negative. Average crop yield by the 2030s decreases by 7.5±16.7% under *CC*: yields of groundnut, millet, sorghum and maize decrease between 5.4% and 12.3% in the ensemble median. In contrast, yield of cotton, rice and cassava increase by between 5% and 13.2%. Under $CC_{w/oCO2}$, average crop yield decreases by 8.5±9.9%, with maize experiencing the largest decrease (-8.8±14.7%) (Figure 4 and Table A2).

[4] The sum does not equal 100 because values represent the median across the five GCMs, which disagree in some places with respect to the overall desert/semi-arid areas.

Figure 4: Similar to Figure 3 for Senegal for the top-five crops harvested in semi-arid areas



Note: Maize includes 30 simulations (6GGCMsx5GCMs); millet and groundnut include 10 simulations (2GGCMsx5GCMs); sorghum and cotton include 5 simulations (1 GGCMx5GCMs).

Source: author

Table 4: Share of Köppen-Geiger climatic zone areas in the PRISE countries in the year 2000 and 2030 (%)

Country	Köppen-Geiger Climatic Zone	2000	2030
Senegal	Tropical Savannah	34.0±8.0	31.3±24.2
	Hot Desert	17.4±8.0	17.4±15.9
	Hot Semi-Arid	43.2±6.1	43.1±2.4
Burkina Faso	Tropical Savannah	61.1±6.8	70.3±8.5
	Hot Semi-Arid	38.9±3.4	29.7±8.5
Kenya	Tropical Rainforest		1.0±1.5
	Tropical Monsoon	1.0±1.5	2.6±0.8
	Tropical Savannah	36.9±5.3	49.2±7.6
	Hot Desert	17.9±6.1	7.7±7.6
	Hot Semi-Arid	34.9±2.3	35.4±6.8
	Temperate – Dry/Warm Summer	0.5±0.8	0.5±0.0
	Temperate – w/o dry season/Warm Summer	9.2±0.8	7.7±0.0
Tanzania	Tropical Rainforest	0.3±0.0	
	Tropical Monsoon	1.3±0.5	1.3±0.5
	Tropical Savannah	86.1±0.9	90.2±1.4
	Hot Semi-Arid	3.5±0.5	4.1±2.3
	Temperate – w/o dry season/Hot Summer	3.2±0.5	1.6±0.0
	Temperate – w/o dry season/Warm Summer	3.5±0.5	1.6±0.5
	Temperate – Dry Winter/Hot Summer	0.3±0.5	0.3±0.5
	Temperate – Dry Winter/Warm Summer	0.6±0.5	0.3±0.0
Pakistan	Hot Desert	61.8±3.0	64.5±5.2
	Cold Desert	5.2±0.2	2.2±1.5
	Hot Semi-Arid	10.7±1.8	11.6±5.5
	Cold Semi-Arid	6.2±0.3	6.5±1.5
	Temperate – w/o dry season/Hot Summer	3.4±0.4	5.7±0.8
	Temperate – w/o dry season/Warm Summer	0.3±0.0	0.3±0.4
	Temperate – Dry Winter/Hot Summer	1.1±1.3	0.6±0.8
	Temperate – Dry Winter/Warm Summer		0.3±0.0
	Cold – Dry Winter/Warm Summer	0.6±0.4	0.8±0.4
	Cold – Dry Winter/Cold Summer	0.5±0.4	0.3±0.4
	Cold – w/o dry season/Warm Summer	3.3±0.0	3.9±0.8
	Cold – w/o dry season/Cold Summer	2.2±0.4	0.8±0.0
	Polar Tundra	1.1±0.4	0.8±0.0
Tajikistan	Cold Desert	6.7±0.0	10.1±2.4
	Hot Semi-Arid		5.1±2.5
	Cold Semi-Arid	16.7±0.1	16.6±2.5
	Temperate – w/o dry season/Hot Summer	6.7±2.5	5.0±2.4

Country	Köppen-Geiger Climatic Zone	2000	2030
Tajikistan	Cold – w/o dry season/Hot Summer	1.6±0.1	4.9±2.5
	Cold – w/o dry season/Warm Summer	23.2±2.4	28.2±2.5
	Cold – w/o dry season/Cold Summer	23.4±2.4	23.4±2.5
	Polar Tundra	18.4±2.5	8.3±2.5

Note: Values correspond to the median in the GCM ensemble; the range is the MAD.

Source: author

4.2 Burkina Faso

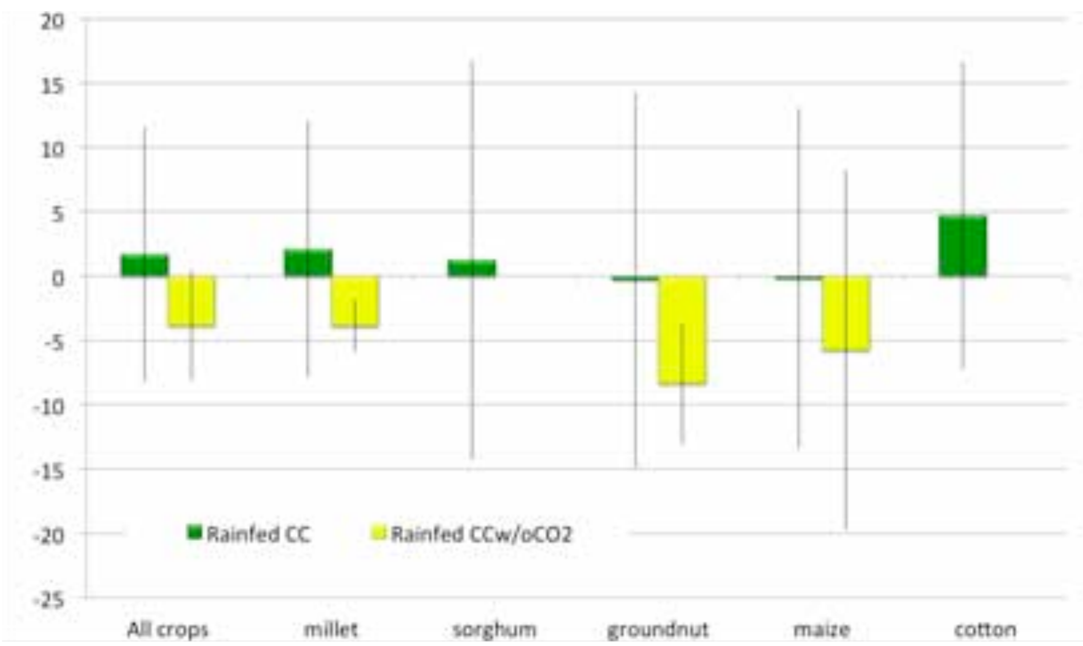
Burkina Faso is a low-income economy. Agriculture contributes to 35% of its GDP, and 72% of its population, which counts 17.3 million, lives in rural areas (World Bank, 2014). Burkina Faso is the second PRISE country located in West Africa, just south of the Sahel. Like Senegal's, the climate of Burkina Faso is hot and dry, with 39±3% of the country classified as hot semi-arid and 61±7% as tropical savannah (Table 4).

By the 2030s, 8-73% of current semi-arid areas become tropical savannah according to four GCMs (GFDL-ESM2M, IPSL-CM5A-LR, NorESM1-M and MIROC-ESM-CHEM) predicting wetter conditions; yet 15% of current tropical savannah areas turn semi-arid according to HadGEM2-ES, predicting dryer conditions (Table 4).

Cropland covers 43% of the total land surface, with 42% located in current semi-arid areas. Sorghum and millet are the dominant crops in terms of harvested areas, accounting for 78% of total crop harvested areas in the country. Maize accounts for another 22% of total harvested areas. Other notable crops for the country's economy include cotton and sugarcane (FAO, 2014). These crops are all exclusively rainfed, except rice, which can be found irrigated in only 7% of rice harvested areas. Groundnut is the third most important crop grown in the semi-arid areas of Burkina Faso, after sorghum and millet. Maize remains an important crop grown in this climatic zone as well (Table A2).

By the 2030s, overall crop yield in the semi-arid areas of Burkina Faso increases by 1.7±9.9% under *CC* but decreases by 3.9±4.3% under $CC_{w/oCO2}$. Under *CC*, the sign of change in yield of maize and groundnut varies widely across simulations, resulting in only a slight decrease in the ensemble median, with a large range of negative and positive impacts (-0.2±13.2% and -0.3±14.2%, respectively). Impact on rice yield is positive under *CC* (+10.1±17.6% when rainfed and +3.1±9.9% when irrigated). Without CO_2 effects, yield of all crops, except sugarcane, decrease between -3.7±6.8% for rice and -8.4±4.8% for groundnut. Yield of millet and sorghum increase by 2.1±10% and 1.2±15.5%, respectively, under *CC* – but decrease without CO_2 (Figure 5 and Table A2)

Figure 5: Similar to Figure 3 for Burkina Faso for the top-five crops harvested in the semi-arid areas



Note: Maize includes 30 simulations (6GGCMsx5GCMs); millet and groundnut include 10 simulations (2GGCMsx5GCMs); sorghum and cotton include 5 simulations (1 GGCMx5GCMs).

Source: author

4.3 Kenya

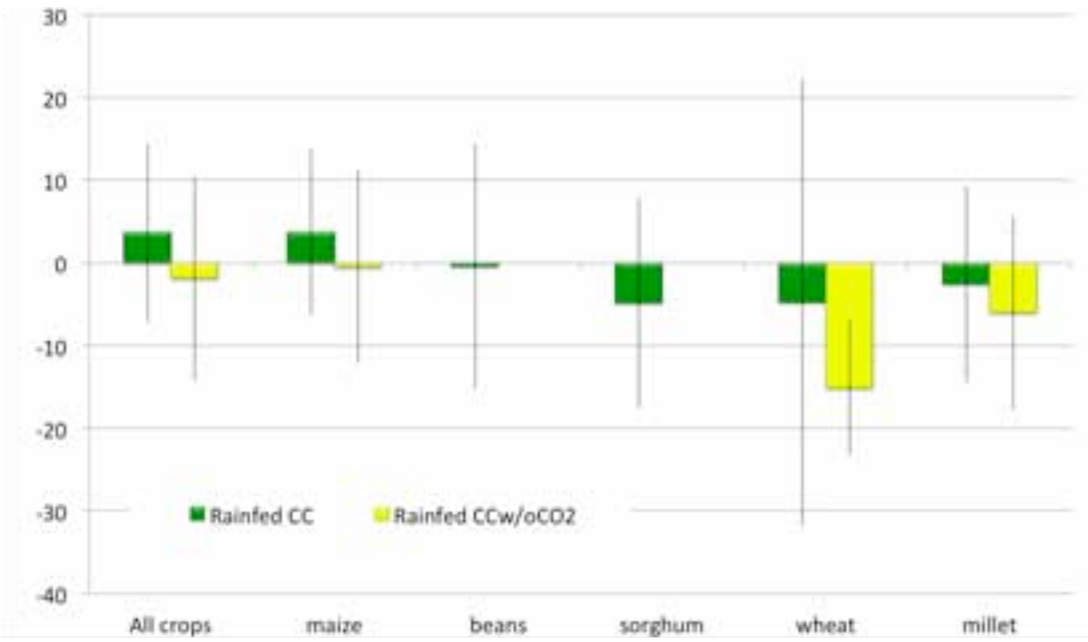
Kenya is a low-income economy, with 30% of its GDP coming from the agriculture sector. Kenya's population counts 45 million people, most of whom live in rural areas (75%) (World Bank, 2014). Located just south of the African horn on the East coast, the climate of Kenya is principally hot semi-arid in the north and northeast (35±2%) and tropical savannah along the coast (37±5%). A small area of the country (9±1%) benefits from temperate climatic condition (Table 4).

By the 2030s, a large share of current semi-arid areas in Kenya could become wetter – that is, tropical savannah: more than 43-45% under IPSL-CM5A-LR and GFDL-ESM2M and about 21-22% under MIROC-ESM-CHEM and NorESM1-M. HadGEM2-ES, on the contrary, indicates a dryer climate, with 16% of current tropical savannah to become hot-semi-arid (Table 4).

Cropland covers 47% of the total country's area. Important crops include maize (53% of total crop harvested areas) and beans (28% of total crop harvested areas), produced in rainfed conditions. Other valuable crops include wheat, potato and sugarcane as well as cash crops such as tea, coffee and mango (FAO, 2014). Along with maize, beans and wheat, sorghum and millet are also important crops grown in semi-arid areas (Table A2).

Overall crop yield in semi-arid areas increases by 3.6±10.8% under *CC* but decreases by 1.9±12.4% under $CC_{w/oCO2}$. Wheat along with sorghum is the most negatively impacted crop: even under *CC*, yield of these crops decrease by 4.8±27% and 4.8±12.7%, respectively. The range of impact is much higher for wheat, which includes the full ensemble of simulations, whereas sorghum was simulated only by EPIC. Yield of beans, as simulated by EPIC, decreases by 0.4±14.8% under *CC*. The spread here results from differences in the climate inputs. Both yield of cassava and sugarcane increase with and without CO_2 effects (Figure 6 and Table A2).

Figure 6: Similar to Figure 3 for Kenya for the top-five crops harvested in semi-arid areas



Note: Wheat and maize include 30 simulations (6GGCMsx5GCMs); millet includes 10 simulations (2GGCMsx5GCMs); sorghum and beans include 5 simulations (1 GGCMx5GCMs).

Source: author

4.4 Tanzania

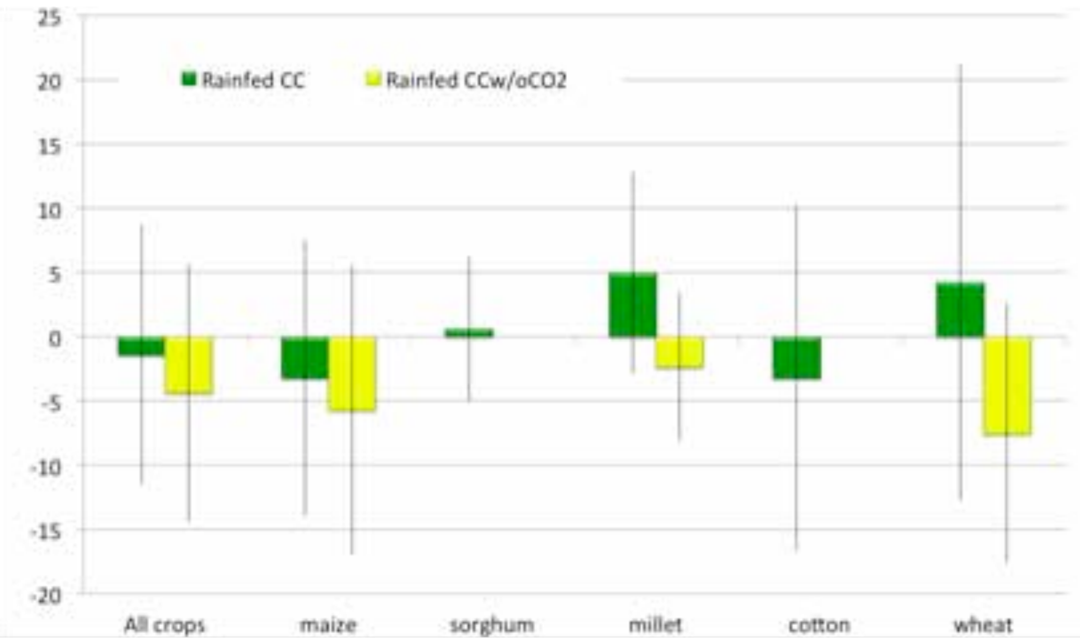
Tanzania is a low-income economy. Agricultural activities contribute to 27% of its GDP. The rural population accounts for 70% of its 47.4 million people (World Bank, 2014). Tanzania is mostly a tropical country: 86±1% of the country's area is tropical savannah; only 4±1% is hot semi-arid and 7±1% is temperate with a hot summer (Table 4).

By the 2030s, temperature increases lead to 35-69% of temperate climatic zone in the highland becoming tropical savannah. In the case of IPSL-CM5A-LR, semi-arid areas in Tanzania disappear to the profit of tropical savannah. As well, GFDL-ESM2M, NorESM1-M and MIROC-ESM-CHEM all predict slightly wetter scenarios leading to a small decrease in current semi-arid areas (to become tropical savannah). HadGEM2-Es, however, predicts a slightly dryer scenario, leading to 5% of current tropical savannah becoming semi-arid (Table 4).

Cropland covers 41% of the total country's area. Altogether, maize, sorghum, cassava and beans account for 73% of total crop harvested areas. Rice and sorghum cover another 18% of total harvested areas. These crops are mostly grown under rainfed conditions. Maize, sorghum and millet are the most important crops grown in semi-arid areas of Tanzania (Table A2).

Overall yield in semi-arid areas decreases by 1.4±10.1% under *CC* and by 4.4±10% under $CC_{w/oCO2}$. Maize yield decreases with and without CO_2, by 3.2±10.7% and 5.2±11.3%, respectively. Wheat yield increases by 4.2±16.9% under *CC* and decreases by 7.6±10.1% under $CC_{w/oCO2}$. Yield of sorghum, estimated only by EPIC under *CC*, remains close to the baseline estimate: 0.6±5.6%. Yield of millet increases by 5±7.9% under *CC* but decreases by 2.4±5.8% under $CC_{w/oCO2}$ (Figure 7 and Table A2).

Figure 7: Similar to Figure 3 for Tanzania for the top-five crops harvested in semi-arid areas



Note: Wheat and maize include 30 simulations (6GGCMsx5GCMs); millet includes 10 simulations (2GGCMsx5GCMs); sorghum and cotton include 5 simulations (1 GGCMx5GCMs).

Source: author

4.5 Pakistan

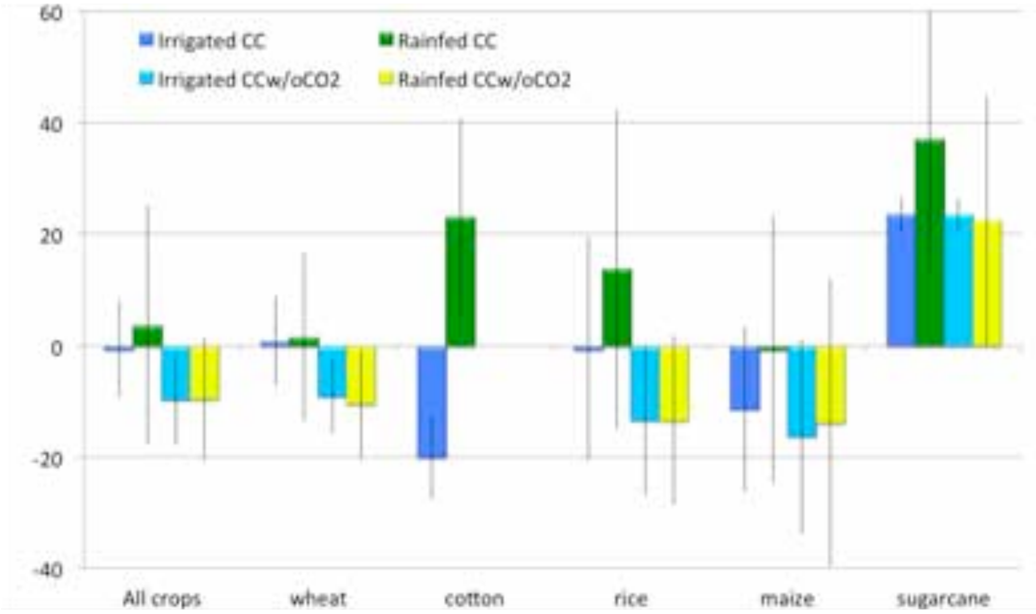
Pakistan is a lower-middle-income economy. The agriculture sector contributes to 25% of GDP. Pakistan is the most populated among the PRISE countries, with 196 million people, 62% of them rural (World Bank, 2014). Located in Central Asia, Pakistan's climate is very dry, ranging across diverse hot (in the southern part) and cold (in the northern part) climatic conditions. Climatic zones include hot desert (62±3%), cold (11±6%) and hot (6±0%) semi-arid areas, cold without a dry season (6±0%), cold desert (5±0%) and temperate (5±1%) and polar tundra (1±0%) (Table 4).

The climate of Pakistan becomes hotter by the 2030s. GFDL-ESM2M and NorESM1-M suggest a dryer climate, with 32-55% of semi-arid areas becoming desert and 10-15% of current temperate zones becoming semi-arid. HadGEM2-ES and MIROC-ESM-CHEM predict a slightly wetter climate, with desert shifting to semi-arid and semi-arid shifting to temperate climate. IPSL-CM5A-LR also predicts 13% of current semi-arid areas becoming temperate. Yet 18% of current temperate areas could also become semi-arid (Table 4).

Cropland covers 34% of the total country's area. Fields of wheat, cotton and rice dominate the rural landscape in Pakistan (FAO, 2014). Wheat harvested area amounts to 49% of total crop harvested areas, followed by cotton (17%) and rice (14%). Wheat and rice are heavily irrigated (68 and 69% of harvested area, respectively). Maize harvested area amounts to only 6% of total crop harvested area, with 41% irrigated. A total of 10% of pea harvested area is also irrigated. Sugarcane is also an important crop grown in the semi-arid areas of Pakistan (Table A2).

Overall crop yield in rainfed semi-arid areas increases by 3.6±21.5% under *CC*. However, results indicate corresponding irrigated yield decreases by 9.6±11.1%. Without CO_2, yield of both rainfed and irrigated crops decrease by 8.6±9.2% and 8±16.3%, respectively. Results show small increases in the ensemble median for wheat under CO_2 (0.8±7.8% for irrigated simulations and 1.5±15.0% for rainfed simulations). Yield of rice and maize decrease for irrigated simulations by 0.7±19.9% and 11.4±14.8%, respectively. Larger decreases are found under $CC_{w/oCO2}$: 13.4±15.2% and 16.3±25.7%, respectively. Yield of sugarcane, however, greatly increases (36.9±23.7% under *CC* and 22.4±22.3% under $CC_{w/oCO2}$) (Figure 8 and Table A2).

Figure 8: Similar to Figure 3 for Pakistan for the top-five crops harvested in the semi-arid areas



Note: Wheat and maize include 30 simulations (6GGCMsx5GCMs); rice includes 25 simulations (5GGCMsx5GCMs); sugarcane includes 10 simulations (2GGCMsx5GCMs); cotton includes 5 simulations (1 GGCMx5GCMs).

Source: author

4.6 Tajikistan

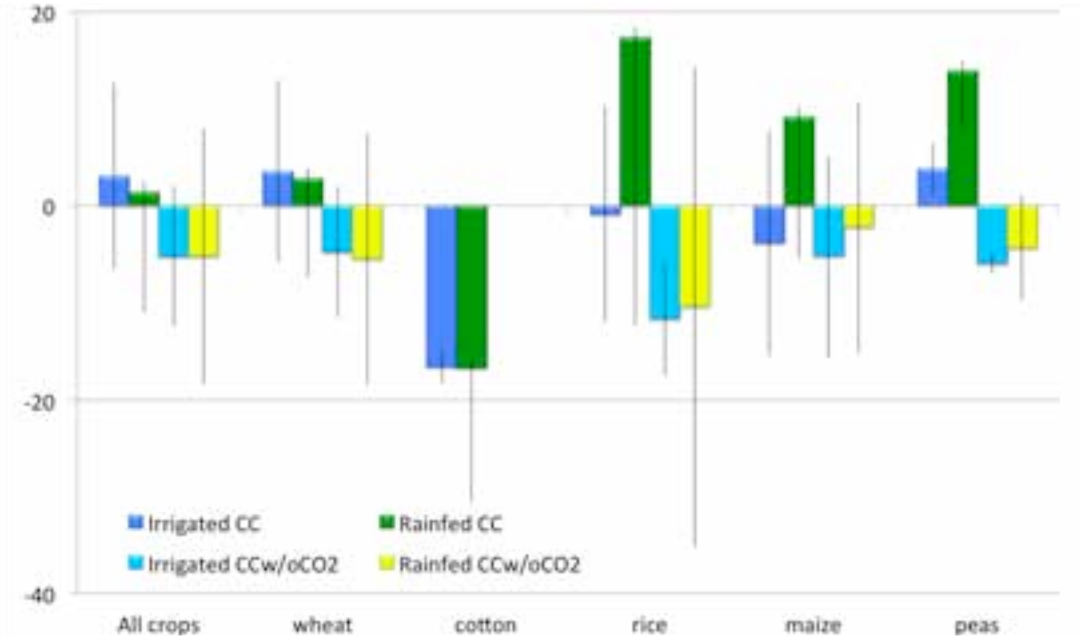
Tajikistan is a low-income economy. A total of 70% of the population lives in rural areas. The agriculture sector contributes to 27% of its GDP (World Bank, 2014). Tajikistan's climate is cold and dry: 48±8% is classified as cold without a dry season, 7±0% as cold desert, 17±0% as cold semi-arid, 18±3% as polar tundra and 7±3% as temperate with a hot summer but without a dry season (Table 4).

By the 2030s, a large share of current temperate zones in Tajikistan could become semi-arid according to HadGEM2-ES (25%), MIROC-ESM-CHEM (40%), NorESM1-M (50%) and IPSL-ESM2M (67%). IPSL-ESM2M even predicts that 18% of current semi-arid areas could dry out and become desert. Cold climatic regions decrease under all GCM scenarios up to 30.2% under HadGEM2-ES (Table 4).

Cropland covers 34% of the total country's area. Wheat and cotton cover 95% of crop harvested areas in Tajikistan. Wheat is mostly grown under rainfed condition, with only 14% irrigated. Only 3% of cotton harvested area is irrigated. In addition to wheat and cotton, rice and maize are also relatively important crops grown in semi-arid lands. Crops grown in semi-arid areas are largely irrigated: irrigated wheat accounts for 35% of total wheat harvested areas. Similarly, irrigated maize accounts for 56% and irrigated rice for 66% (Table A2).

Overall, rainfed crop yield in semi-arid areas increase by 1.4±12.5% under *CC* and decrease by 5.2±13.2% under $CC_{w/oCO2}$. Similarly to Pakistan, irrigated yield decreases by 1.1±10.9% under *CC* and by 6.5±7.8% under $CC_{w/oCO2}$. Wheat, in particular, may benefit from longer growing seasons as temperatures rise. Wheat yield increases by 2.8±10.2% and 3.5±12.9% under rainfed and irrigated conditions, respectively, when taking into account CO_2 effects. Under $CC_{w/oCO2}$, wheat yield decreases by 5.5±12.9% and 4.8±6.8% under rainfed and irrigated conditions, respectively. Yield of maize and rice increase in rainfed areas (by 17.4±29.9% and 9.1±14.6%, respectively) but decrease in irrigated croplands under *CC* (by -0.9±11.1% and -3.9±11.6%, respectively). Finally, both irrigated and rainfed yield of these crops decrease under $CC_{w/oCO2}$ by -11.7±5.8% and -10.4±24.8% for irrigated and rainfed rice; and by -5.2±10.4% and -2.2±12.9% for irrigated and rainfed maize (Figure 9 and Table A2).

Figure 9: Similar to Figure 3 for Tajikistan for the top-five crops harvested in semi-arid areas



Note: Wheat and maize include 30 simulations (6GGCMsx5GCMs); rice includes 25 simulations (5GGCMsx5GCMs); cotton and peas includes 5 simulations (1 GGCMx5GCMs).

Source: author

5. Discussion

5.1 Biophysical drivers of crop yield change

Changes in temperature, rainfall and CO_2 concentrations are the main drivers of changes in crop yield. Atmospheric CO_2 concentrations are projected to reach 450 parts per million (ppm) in the 2030s under RCP 8.5. Thus CO_2 effects could play a central role in stimulating rates of photosynthesis and reduce water demand of crops, the latter being particularly important in rainfed systems (Deryng, 2014). Yet the spread of simulated yield is much larger when including CO_2 effects, as GGCMs tend to produce large differences in their response.

Impacts on crop yield in the African countries, where crops are generally grown under rainfed conditions, tend to be negative, with Tanzania and Senegal the most negatively impacted countries. Small increases in median crop yield occur but are associated with a large range of yield changes spanning both negative and positive values. In Tajikistan and Pakistan, where irrigation is applied over large areas, uncertainties tend to be larger for rainfed systems. Yield of wheat, a key crop in these countries, decreases without the effects of elevated CO_2 under both irrigated and rainfed conditions. Carbon fertilisation could possibly alleviate some of these losses. The wide range of results found for each country and crop type owes to differences in climate scenarios between GCMs and differences in GGCMs sensitivity to changes in temperature, precipitation, radiation and CO_2.

In this assessment, several important crops for semi-arid areas and the PRISE countries were simulated by only one or two GGCMs. As differences between crop model simulations can be much larger because of differences in crop model simulations than because of differences in climate model simulations (Deryng, 2014), results for crops such as millet, sorghum, cassava, cotton, sugarcane, etc. are less robust than those for wheat, maize and rice, which nearly all the GGCMs simulated. Yet the use of this subset of simulations enables a more comprehensive assessment of climate impacts on crop yield in global semi-arid regions.

The crop models in ISI-MIP are global and they are developed to simulate global patterns of yield under climate change; the GGCMs are not rigorously calibrated to simulate regional yield in the PRISE countries. Each model was developed and validated against global crop yield independently prior to the ISI-MIP study. Additionally, although the experimental design and climate scenarios in ISI-MIP were meant to harmonise simulations, several differences and caveats remain, especially related to the parameterisation of CO_2 response and the role of nitrogen fertiliser. For more detailed information on the calibration and validation methods, please see Table S5 of Rosenzweig et al. (2014).[5] Therefore, these results should be interpreted with caution. Furthermore, crop model performance on less widely grown crops, and where only one or two GGCMs are available, should also be treated with caution. Crops such as cassava and millet are under-studied in the literature and observational data are limited to validate simulations.

ISI-MIP provided the first model intercomparison analysis across multiple sectors of climate impacts

"…CO_2 effects could play a central role in stimulating rates of photosynthesis and reduce water demand of crops, the latter being particularly important in rainfed systems (Deryng, 2014)."

[5] Freely available at www.pnas.org/content/suppl/2013/12/16/1222463110.DCSupplemental/sapp.pdf

and enabled a systematic identification of specific sources of uncertainties and model weaknesses, necessary for addressing model limitations and facilitating further improvement initiatives. Evaluation and improvement of gridded agricultural data and crop models are currently being addressed in AgMIP on-going work (Elliott et al., 2014).

5.2 Irrigation water availability

Crop simulations in ISI-MIP include rainfed and fully irrigated simulations on all suitable crop-growing areas defined by each GGCMs according to agro-climatic parameters such as crop-specific temperature and soil moisture thresholds. These gridded results were processed to focus on current rainfed and irrigated growing areas using global masks of rainfed and irrigated cropping areas for the year 2000 (Portmann et al., 2008). Irrigated and rainfed areas were held constant to the present day. Furthermore, although climate change may reduce water resources, thus threatening irrigated crop yield, no account was made of future changes in water availability in all the irrigated simulations.

As illustrated by the yield impact barplots, irrigation will not necessarily counteract the negative impacts of climate change. In fact, in several instance, we find that yield of irrigated crops could decrease even more in absolute terms than that of rainfed crops as a result of extreme temperature stress, which could totally cancel out the benefits of irrigation. Elevated temperatures affect crops non-linearly: when temperatures reach a certain threshold, yield can decrease dramatically.

A false colour image of flooding in Pakistan, August 4, 2010, Kheshgi, KPK.

Kabul River: pale green. Buildings and raods: silver. Turquoise blue: shallow, muddy water or water-logged ground. Brown and tan: bare ground in the hills. Red: plant-covered land. Geometric shapes under the water near the river are probably submerged fields of crops.

6. Conclusion

2DU Kenya, Mount Kenya region.

This study synthesised results from a large modelling intercomparison exercise using state-of-the-art crop and climate models. Changes in the extent of semi-arid areas vary moderately across climate scenarios, especially in western Sub-Saharan Africa. The resulting impacts on crop yield vary largely across crop models and climate scenarios. Overall, crop yield of major crops grown in semi-arid areas are negatively impacted by climate change owing to increases in extreme temperatures affecting both irrigated and rainfed cropping systems. By the 2030s, models predict generally a wetter climate that mostly benefits rainfed crop production since irrigated crops already have sufficient water. Both rainfed and irrigated crops are vulnerable to extreme temperature stress. In the case of rainfed conditions, results indicate effects of reductions in water stress from a wetter climate are greater than those of increases in temperature stress. Irrigated yield (which comprise primarily wheat, rice and maize grown in Central Asia) show overall decreases as a result of temperature stress.

Elevated CO_2 could play a key role in reducing some of the negative impacts, which in some cases could lead in an overall increase in crop yield. CO_2 effects are particularly important in rainfed cropland, where elevated CO_2 concentrations not only stimulate photosynthesis but also improve crop water use by reducing water loss through transpiration. Yet actual realisation of carbon fertilisation on crop yield remains largely uncertain as experimental studies have yet to be carried on in semi-arid croplands (Leakey et al., 2012).

Results presented here offer a consistent and comprehensive impact assessment of near-term climate change effects on the extent of semi-arid areas and crop yield across semi-arid regions of the world and provide insight on regional impacts in the selected PRISE countries. These results should be considered with caution: important limitations and uncertainties exist with respect to crop interaction with agro-climatic factors (e.g. carbon, temperature, water, nitrogen). Results presented here, in addition to providing an assessment of median impacts, offer an evaluation of the range of uncertainties related to global crop climate simulations.

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Appendix

Tables A1-A4

Appendix

Table A1: Description of Köppen climate symbols and defining criteria. Reproduced from Table 1 (Peel et al., 2007)

1st	2nd	3rd	Description	Criteria*
A			Tropical	$T_{cold} \geq 18$
	f		- Rainforest	$P_{dry} \geq 60$
	m		- Monsoon	Not (Af) & $P_{dry} \geq 100 – MAP/25$
	w		- Savannah	Not (Af) & $P_{dry} < 100 – MAP/25$
B			Arid	$MAP < 10 \times P_{threshold}$
	W		- Desert	$MAP < 5 \times P_{threshold}$
	S		- Steppe	$MAP \geq 5 \times P_{threshold}$
		h	- Hot	$MAT \geq 18$
		k	- Cold	$MAT < 18$
C			Temperate	$T_{hot} > 10$ & $0 < T_{cold} < 18$
	s		- Dry Summer	$P_{sdry} < 40$ & $P_{sdry} < P_{wwet}/3$
	w		- Dry Winter	$P_{wdry} < P_{swet}/10$
	f		- Without dry season	Not (Cs) or (Cw)
		a	- Hot Summer	$T_{hot} \geq 22$
		b	- Warm Summer	Not (a) & $T_{mon10} \geq 4$
		c	- Cold Summer	Not (a or b) & $1 \leq T_{mon10} < 4$
D			Cold	$T_{hot} > 10$ & $T_{cold} \leq 0$
	s		- Dry Summer	$P_{sdry} < 40$ & $P_{sdry} < P_{wwet}/3$
	w		- Dry Winter	$P_{wdry} < P_{swet}/10$
	f		- Without dry season	Not (Ds) or (Dw)
		a	- Hot Summer	$T_{hot} \geq 22$
		b	- Warm Summer	Not (a) & $T_{mon10} \geq 4$
		c	- Cold Summer	Not (a, b or d)
		d	- Very Cold Winter	Not (a or b) & $T_{cold} < –38$
E			Polar	$T_{hot} < 10$
	T		- Tundra	$T_{hot} > 0$
	F		- Frost	$T_{hot} \leq 0$

Note: *MAP = mean annual precipitation, MAT = mean annual temperature, Thot = temperature of the hottest month, Tcold = temperature of the coldest month, Tmon10 = number of months where the temperature is above 10, Pdry = precipitation of the driest month, Psdry = precipitation of the driest month in summer, Pwdry = precipitation of the driest month in winter, Pswet = precipitation of the wettest month in summer, Pwwet = precipitation of the wettest month in winter, Pthreshold = varies according to the following rules (if 70% of MAP occurs in winter then Pthreshold = 2 x MAT, if 70% of MAP occurs in summer then Pthreshold = 2 x MAT + 28, otherwise Pthreshold = 2 x MAT + 14). Summer (winter) is defined as the warmer (cooler) six month period of ONDJFM and AMJJAS.

Table A2: Summary of relative change in crop yield in the 2030s relative to the 2000s in semi-arid areas globally and in PRISE countries for all crops analysed here

Country	Crop	Total Harvest Area	Rainfed Area	Irrigated area	% irrigated area	Irrigated Yield CC	Rainfed Yield CC	Irrigated Yield CC w/o CO2	Rainfed Yield CC w/o CO2
Global	All crops	77,478,739±6,976,277	62,327,571±5,293,230	14,446,138±1,672,162	18.6	-1.1±5	4.7±9.6	-7.1±3.8	-4.5±7.3
	wheat	22,643,539±1,702,476	12,548,852±536,107	9,461,752±938,390	41.8	-1.2±4.7	4.2±8.7	-7.7±3.9	-6.8±4.6
	millet	13,253,066±1,120,341	13,233,543±1,118,787	19,523±1,554	0.1	8.7±3.7	5.8±8.1	8.4±3.8	-0.9±3.2
	sorghum	9,706,089±943,465	9,684,884±943,622	21,205±3,722	0.2	-7.2±1.3	-0.5±1.2		
	cotton	7,081,389±561,649	6,973,827±558,719	107,561±4,955	1.5	-9.5±6.1	-1.4±25.1		
	maize	6,132,660±387,500	5,190,108±324,660	975,377±48,666	15.9	-2.1±2.6	5±6.8	-3.9±4.8	-1.5±4.7
	groundnut	6,004,865±541,980	5,987,747±542,482	17,456±2,071	0.3	-1.6±15.3	-0.4±12	-5.4±0.6	-5.2±6.1
	rice	5,672,274±602,584	1,841,263±184,051	3,719,550±655,285	65.6	1.2±7.1	7.9±11.6	-7.1±3.5	-3.9±4.5
	beans	3,594,965±539,054	3,569,138±523,477	29,547±3,771	0.8	4.4±1.6	7±14		
	sunflower	1,429,214±75,129	1,422,255±75,539	6,682±410	0.5	7.6±2	26.6±28.3	-4.7±0.3	-4.9±0.4
	sugarcane	1,083,650±211,776	1,059,856±201,935	24,118±8,199	2.2	7.2±0.6	22.4±5.7	7.1±0.7	11.8±6.2
	soy	389,584±165,593	336,958±160,751	55,066±3,617	14.1	5.4±9.5	15.4±18.8	-5.4±5.3	-1±9.6
	peas	263,621±45,288	255,351±43,661	8,270±1,518	3.1	2.4±2.7	10.4±6.6	-6.3±2.9	-7.6±4.7
	cassava	223,824±79,443	223,789±79,439	30±4	<0.1	4.2±3.2	7.6±19	-11.1±1.9	-1.5±5.8
Senegal	All crops	866,137±237,788	865,665±237,598	215±93	<0.1	1.1±8.8	-7.5±16.7	-6.7±8.4	-8.5±9.9
	groundnut	380,872±118,585	380,872±118,585				-5.7±22.2		-8.5±3.7
	millet	351,747±74,362	351,747±74,362				-6±12.4		-6.5±10.6
	sorghum	66,209±15,476	66,208±15,476	1±0	<0.1	-7.1±7.3	-12.3±18.5		
	maize	37,530±20,288	37,471±20,264	59±25	0.2	-4.6±9.4	-5.4±14.9	-5.8±6.9	-8.8±14.7
	cotton	9,923±5,667	9,923±5,667				13.2±13.9		
	rice	9,414±2,089	9,003±1,924	154±68	1.6	2.6±6.6	5±13.4	-6.6±6	-4.5±8.7
	cassava	9,399±1,295	9,397±1,294	2±0	<0.1	5.3±3.7	8.4±33.3	-6.1±2	9.5±8.8
	peas	533±0	533±0				5.8±28.1		-10±18.1
	sugarcane	509±26	509±26	<1	<0.1	-3.1±0	10.9±19.2	-3.2±0	4.9±18.9
Burkina Faso	All crops	1,132,456±108,566	1,132,262±108,542	194±1	<0.1	2.5±9.1	1.7±9.9	-6.3±4.1	-3.9±4.3
	millet	545,646±14,436	545,646±14,436			-3.4±2.3	2.1±10	-4.3±0.8	-3.9±2
	sorghum	450,950±65,981	450,950±65,981			-4.9±2.4	1.2±15.5		
	groundnut	72,380±16,324	72,380±16,324			2.3±14.8	-0.3±14.6	-6±0.7	-8.4±4.8

Country	Crop	Total Harvest Area	Rainfed Area	Irrigated area	% irrigated area	Irrigated Yield CC	Rainfed Yield CC	Irrigated Yield CC w/o CO2	Rainfed Yield CC w/o CO2
	maize	44,399±8,000	44,366±8,000	33±1	0.1	-5.3±8.4	-0.2±13.2	-5.6±6.2	-5.8±14
	cotton	13,022±2,879	13,022±2,879				4.7±11.9		
	rice	6,042±945	5,881±922	161±0	2.7	3.1±9.9	10.1±17.6	-7±5	-3.7±6.8
	sugarcane	18±0	18±0	<1	0.3	-6.5±1.6	21.4±2	-6.5±1.5	16.6±0.5
Kenya	All crops	915,591±110,775	915,154±109,787	461±138	0.1	-2.0±7.1	3.6±10.8	-3.1±5.1	-1.9±12.4
	maize	479,083±60,362	478,653±59,378	453±137	0.1	-2±7.4	3.7±10	-3.1±5	-0.5±11.6
	beans	249,453±31,634	249,453±31,634				-0.4±14.8		
	sorghum	62,632±4,558	62,632±4,558				-4.8±12.7		
	wheat	44,589±5,374	44,589±5,374				-4.8±27		-15.1±8.1
	millet	37,501±3,181	37,501±3,181				-2.5±11.9		-6±11.6
	cassava	14,924±2,082	14,924±2,082				32.7±27.5		8.5±4.5
	sugarcane	11,368±1,814	11,368±1,814				32.4±5.9		19±7.2
	cotton	8,336±1,405	8,329±1,401	7±0	0.1	-6.6±4.5	-6.3±12.8		
	groundnut	7,270±190	7,270±190				0.5±20.1		-3.6±12.2
	sunflower	197±89	197±89				10.5±15.7		-22.3±27.2
	rice	162±86	162±86				7.4±18		-7.9±11.7
	peas	76±0	76±0				12.1±12.9		-2±16.4
Tanzania	All crops	76,980±28,876	76,943±22,770	36±54	<0.1	-1.7±3.4	-1.4±10.1	-3±3.9	-4.4±10
	maize	28,611±20,598	28,576±14,833	35±52	0.1	-1.9±4.8	-3.2±10.7	-3.4±5.3	-5.7±11.3
	sorghum	20,390±562	20,390±562				0.6±5.6		
	millet	19,257±696	19,257±696				5±7.9		-2.4±5.8
	cotton	3,321±2134	33,20±2076	2±2	<0.1	-6.3±1.3	-3.2±13.5		
	wheat	1,895±970	1,895±970				4.2±16.9		-7.6±10.1
	cassava	1,389±1153	1,389±1153				29.5±22.4		18.7±5.1
	rice	813±1205	813±922	<1	<0.1	5.1±6.6	2.7±7.6	-1.9±4.8	-3.8±5.6
	groundnut	750±735	750±735				-0.2±13.6		-4.4±7.6
	sunflower	287±425	287±425				4.8±3.8		-6.9±2.5
	peas	136±201	136±201				7.5±3.4		-6.8±3.1
	beans	132±196	132±196				4.9±2.1		
Pakistan	All crops	4,144,983±374,838	2,311,831±148,913	1,824,197±104,325	44	-0.7±8.6	3.6±21.5	-9.7±8.2	-9.6±11.1

Country	Crop	Total Harvest Area	Rainfed Area	Irrigated area	% irrigated area	Irrigated Yield CC	Rainfed Yield CC	Irrigated Yield CC w/o CO2	Rainfed Yield CC w/o CO2
	wheat	2,110,746±197,844	764,742±25,711	1,343,094±72,427	63.6	0.8±7.8	1.5±15	-9.1±6.7	-10.5±10
	cotton	677,732±56,949	659,880±55,209	17,852±1,346	2.6	-20.1±7.5	22.9±17.9		
	rice	485,847±58,042	163,118±5,987	323,431±23,954	66.6	-0.7±19.9	13.6±28.5	-13.4±13.6	-13.4±15.2
	maize	318,113±10,117	183,630±11,400	127,660±5,943	40.1	-11.4±14.8	-0.7±24	-16.3±17.4	-13.9±25.7
	sugarcane	238,148±15,835	233,222±15,741	4,926±349	2.1	23.4±3.3	36.9±23.7	23.3±3	22.4±22.3
	millet	94,487±7,577	93,849±7,584	643±14	0.7	-1.3±7.5	13±17.6	-2.4±3.1	2±8.1
	sorghum	76,681±9,608	75,397±9,358	1295±74	1.7	-6.5±15.2	9.1±38		
	beans	61,800±9,840	59,182±9,368	2648±110	4.3	1.9±22.6	16.8±35.2		
	groundnut	30,010±1,719	30,010±1,719				17.4±45.4		-2.2±20.6
	peas	26,783±3,876	24,167±3,404	2646±108	9.9	1.9±1.6	10.4±3.1	-5.9±1.9	-5.3±2.5
	sunflower	24,635±3,432	24,634±3,432	1±0	<0.1	3.5±4	29.3±31.7	-8.3±2.7	-9.4±30.8
Tajikistan	All crops	176,497±15,295	130,123±11,693	44,274±1,091	25.1	3±9.6	1.4±12.5	-5.3±7.3	-5.2±13.2
	wheat	99,138±9,004	62,627±5,877	34,665±725	35	3.5±9.5	2.8±10.2	-4.8±6.8	-5.5±12.9
	cotton	68,527±5,752	63,815±5,547	4,574±205	6.7	-16.5±1.7	-16.7±13.9		
	rice	4,825±276	1,592±106	3,161±117	65.5	-0.9±11.1	17.4±29.9	-11.7±5.8	-10.4±24.8
	maize	3,062±181	1,302±83	1,715±33	56	-3.9±11.6	9.1±14.6	-5.2±10.4	-2.2±12.9
	peas	583±82	431±80	152±11	26.1	3.7±2.7	13.9±6.2	-6±1.1	-4.4±5.4
	sunflower	239±0	232±0	6±0	2.7	1.1±6.6	25.9±28.6	-6.5±1	0.1±4.1
	millet	102±0	102±0				4.8±11		-13.1±37.4
	groundnut	15±0	15±0				3.8±19.3		0±4.6
	sorghum	7±0	6±0	1±0	16.3	-17.2±4	0.3±20.7		

Note: Results include rainfed and irrigated yield, with and without CO_2 effects. Median values are reported (%); the range represents spread in the results across all GCM-GGCM simulations. Total harvested, irrigated and rainfed areas are reported (ha) for semi-arid areas exclusively.

Table A3: Summary of relative change in crop yield in the 2050s relative to the 2000s in semi-arid areas globally and in PRISE countries for all crops analysed here

Country	Crop	Total Harvest Area	Rainfed Area	Irrigated area	% irrigated area	Irrigated Yield CC	Rainfed Yield CC	Irrigated Yield CC w/o CO2	Rainfed Yield CC w/o CO2
Global	All crops	77,478,739±6,976,277	62,327,571±5,293,230	14,446,138±1,672,162	18.6	0.5±9.3	4.5±12.8	-13.3±7.2	-12.5±9.5
	wheat	22,643,539±1,702,476	12,548,852±536,107	9,461,752±938,390	41.8	0.5±6.8	5.5±14.1	-13.0±7.2	-15.8±7.7
	millet	13,253,066±1,120,341	13,233,543±1,118,787	19,523±1,554	0.1	13.9±17.3	3.9±4.3	25.8±9.1	-8.5±2.6
	sorghum	9,706,089±943,465	9,684,884±943,622	21,205±3,722	0.2	-19.2±4.1	-9.1±5.8		
	cotton	7,081,389±561,649	6,973,827±558,719	107,561±4,955	1.5	-26.7±2.0	1.1±4.3		
	maize	6,132,660±387,500	5,190,108±324,660	975,377±48,666	15.9	-4.5±6.9	5.5±11.4	-7.1±6.9	-8.6±6.0
	groundnut	6,004,865±541,980	5,987,747±542,482	17,456±2,071	0.3	-4.5±30.8	0.1±27.3	-10.8±2.2	-18.7±5.0
	rice	5,672,274±602,584	1,841,263±184,051	3,719,550±655,285	65.6	2.5±15.6	9.0±21.9	-16.8±5.1	-16.9±8.2
	beans	3,594,965±539,054	3,569,138±523,477	29,547±3,771	0.8	5.2±3.7	4.2±11.5		
	sunflower	1,429,214±75,129	1,422,255±75,539	6,682±410	0.5	11.2±12.8	30.7±28.1	-7.3±3.3	-23.4±6.9
	sugarcane	1,083,650±211,776	1,059,856±201,935	24,118±8,199	2.2	11.8±1.4	48.5±6.3	11.3±2.1	23.7±4.4
	soy	389,584±165,593	336,958±160,751	55,066±3,617	14.1	9.0±14.7	18.1±24.3	-10.6±6.1	-14.3±12.2
	peas	263,621±45,288	255,351±43,661	8,270±1,518	3.1	3.2±3.3	17.9±18.4	-12.7±4.3	-15.4±12.1
	cassava	223,824±79,443	223,789±79,439	30±4	<0.1	10.7±5.9	13.3±38.9	-16.0±1.8	-3.6±5.7
Senegal	All crops	866,137±237,788	865,665±237,598	215±93	<0.1	1.8±15.2	-10.8±21.1	-15.7±13.9	-21.2±13.1
	groundnut	380,872±118,585	380,872±118,585				-9.9±29.5		-21.3±16.6
	millet	351,747±74,362	351,747±74,362				-11.1±11.1		-17.7±17.8
	sorghum	66,209±15,476	66,208±15,476	1±0	<0.1	-17.1±16.2	-20.3±32.9		
	maize	37,530±20,288	37,471±20,264	59±25	0.2	-10.9±10.9	-9.7±17.4	-12.9±13.4	-19.1±16.6
	cotton	9,923±5,667	9,923±5,667				-8.2±28.1		
	rice	9,414±2,089	9,003±1,924	154±68	1.6	6.7±7.4	7.4±21.2	-14.9±8.5	-18.0±17.3
	cassava	9,399±1,295	9,397±1,294	2±0	<0.1	7.3±7.0	18.2±49.6	-14.8±3.4	-3.3±31.8
	peas	533±0	533±0				13.4±14.3		-23.9±12.3
	sugarcane	509±26	509±26	<1	<0.1	-8.3±0.0	13.5±23.0	-8.4±0.0	-0.1±28.9
Burkina Faso	All crops	1,132,456±108,566	1,132,262±108,542	194±1	<0.1	-2.0±15.2	-9.5±14.9	-17.4±6.4	-12.2±4.9
	millet	545,646±14,436	545,646±14,436			-7.4±3.8	-6.4±12.7	-8.5±1.7	-12.0±3.2
	sorghum	450,950±65,981	450,950±65,981			-12.0±4.3	-18.9±2.8		
	groundnut	72,380±16,324	72,380±16,324			-1.8±28.4	-14.4±26.4	-14.7±1.4	-26.0±11.4

Country	Crop	Total Harvest Area	Rainfed Area	Irrigated area	% irrigated area	Irrigated Yield CC	Rainfed Yield CC	Irrigated Yield CC w/o CO2	Rainfed Yield CC w/o CO2
	maize	44,399±8,000	44,366±8,000	33±1	0.1	-11.3±10.1	-10.6±16.8	-14.2±15.7	-15.1±17.3
	cotton	13,022±2,879	13,022±2,879				-13.7±14.5		
	rice	6,042±945	5,881±922	161±0	2.7	-0.6±14.2	-1.5±31.9	-18.3±4.5	-23.0±16.0
	sugarcane	18±0	18±0	<1	0.3	-15.2±3.3	25.9±3.5	-15.0±2.8	14.3±1.8
Kenya	All crops	915,591±110,775	915,154±109,787	461±138	0.1	-5.3±7.9	3.4±20.8	-6.7±9.0	-7.2±14.9
	maize	479,083±60,362	478,653±59,378	453±137	0.1	-5.8±8.3	4.1±14.8	-9.2±10.0	-6.5±13.7
	beans	249,453±31,634	249,453±31,634				-4.1±31.5		
	sorghum	62,632±4,558	62,632±4,558				-13.3±29.1		
	wheat	44,589±5,374	44,589±5,374				-1.3±49.0		-28.1±25.4
	millet	37,501±3,181	37,501±3,181				-1.8±21.8		-13.3±10.2
	cassava	14,924±2,082	14,924±2,082				42.0±56.2		-1.8±6.8
	sugarcane	11,368±1,814	11,368±1,814				40.2±9.9		10.2±5.7
	cotton	8,336±1,405	8,329±1,401	7±0	0.1	-23.0±14.9	-31.1±27.7		
	groundnut	7,270±190	7,270±190				-6.0±31.6		-17.4±10.7
	sunflower	197±89	197±89				20.2±28.4		-34.0±27.5
	rice	162±86	162±86				13.6±27.8		-18.2±14.6
	peas	76±0	76±0				15.6±23.3		-12.5±8.5
Tanzania	All crops	76,980±28,876	76,943±22,770	36±54	<0.1	-2.6±3.7	-1.5±9.7	-5.8±6.5	-7.6±8.1
	maize	28,611±20,598	28,576±14,833	35±52	0.1	-3.9±7.5	-2.6±9.7	-8.2±10.9	-7.5±9.4
	sorghum	20,390±562	20,390±562				14.2±10.1		
	millet	19,257±696	19,257±696				0.6±15.1		-11.8±4.1
	cotton	3,321±2134	33,20±2076	2±2	<0.1	-9.0±7.5	-9.9±10.3		
	wheat	1,895±970	1,895±970				1.3±23.0		-18.0±13.5
	cassava	1,389±1153	1,389±1153				43.1±27.8		20.4±7.8
	rice	813±1205	813±922	<1	<0.1	6.6±6.4	12.3±12.4	-5.6±4.5	-9.1±7.5
	groundnut	750±735	750±735				-2.3±15.2		-15.7±3.3
	sunflower	287±425	287±425				14.8±4.9		-10.3±3.4
	peas	136±201	136±201				17.6±5.0		-11.3±2.3
	beans	132±196	132±196				19.1±4.3		
Pakistan	All crops	4,144,983±374,838	2,311,831±148,913	1,824,197±104,325	44	-2.4±15.0	4.1±25.8	-17.2±13.0	-17.0±19.4
	wheat	2,110,746±197,844	764,742±25,711	1,343,094±72,427	63.6	-0.1±14.2	2.6±24.7	-16.5±12.1	-20.6±17.2

Country	Crop	Total Harvest Area	Rainfed Area	Irrigated area	% irrigated area	Irrigated Yield CC	Rainfed Yield CC	Irrigated Yield CC w/o CO2	Rainfed Yield CC w/o CO2
	cotton	677,732±56,949	659,880±55,209	17,852±1,346	2.6	-42.1±2.7	-26.4±30.6		
	rice	485,847±58,042	163,118±5,987	323,431±23,954	66.6	-6.8±29.3	6.4±43.3	-29.6±22.3	-33.5±23.3
	maize	318,113±10,117	183,630±11,400	127,660±5,943	40.1	-14.8±21.1	0.3±23.9	-18.3±21.5	-15.7±20.7
	sugarcane	238,148±15,835	233,222±15,741	4,926±349	2.1	34.7±7.0	59.2±63.0	34.8±7.0	30.3±55.4
	millet	94,487±7,577	93,849±7,584	643±14	0.7	-8.2±7.2	12.8±9.9	-4.4±2.2	-1.6±9.9
	sorghum	76,681±9,608	75,397±9,358	1295±74	1.7	-35.8±21.2	-13.5±11.2		
	beans	61,800±9,840	59,182±9,368	2648±110	4.3	-7.4±24.8	7.9±11.9		
	groundnut	30,010±1,719	30,010±1,719				7.7±81.8		-35.0±20.9
	peas	26,783±3,876	24,167±3,404	2646±108	9.9	4.6±4.0	11.2±12.0	-9.6±4.1	-12.6±16.7
	sunflower	24,635±3,432	24,634±3,432	1±0	<0.1	4.8±12.3	19.6±46.4	-13.0±1.0	6.2±45.1
Tajikistan	All crops	176,497±15,295	130,123±11,693	44,274±1,091	25.1	5.4±16.3	10.2±17.8	-11.3±13.9	-8.2±11.8
	wheat	99,138±9,004	62,627±5,877	34,665±725	35	5.9±16.5	11.4±19.3	-11.0±14.3	-8.3±11.6
	cotton	68,527±5,752	63,815±5,547	4,574±205	6.7	-33.9±10.4	-20.8±18.7		
	rice	4,825±276	1,592±106	3,161±117	65.5	-4.2±21.7	47.7±48.5	-19.1±8.7	0.9±46.5
	maize	3,062±181	1,302±83	1,715±33	56	-4.6±15.4	36.6±45.8	-8.1±13.3	7.0±16.3
	peas	583±82	431±80	152±11	26.1	5.5±5.8	53.5±15.6	-11.2±2.7	7.9±7.3
	sunflower	239±0	232±0	6±0	2.7	5.6±5.6	109.7±135.8	-15.3±4.1	34.4±26.4
	millet	102±0	102±0				30.9±61.8		140.2±119.7
	groundnut	15±0	15±0				30.3±50.0		-6.3±8.6
	sorghum	7±0	6±0	1±0	16.3	-24.6±9.1	-9.7±8.7		

Note: Results include rainfed and irrigated yield, with and without CO_2 effects. Median values are reported (%); the range represents spread in the results across all GCM-GGCM simulations. Total harvested, irrigated and rainfed areas are reported (ha) for the semi-arid areas exclusively.

Table A4: Summary of relative change in crop yield in the 2080s relative to the 2000s in semi-arid areas globally and in PRISE countries for all crops analysed here

Country	Crop	Total Harvest Area	Rainfed Area	Irrigated area	% irrigated area	Irrigated Yield CC	Rainfed Yield CC	Irrigated Yield CC w/o CO2	Rainfed Yield CC w/o CO2
Global	All crops	77,478,739±6,976,277	62,327,571±5,293,230	14,446,138±1,672,162	18.6	-3.9±14.9	0.8±20.2	-27.2±11.9	-26.0±11.6
	wheat	22,643,539±1,702,476	12,548,852±536,107	9,461,752±938,390	41.8	-2.3±12.6	4.7±15.1	-26.7±10.6	-25.8±12.2
	millet	13,253,066±1,120,341	13,233,543±1,118,787	19,523±1,554	0.1	21.9±35.2	-10.3±14.5	38.7±6.6	-30.0±10.8
	sorghum	9,706,089±943,465	9,684,884±943,622	21,205±3,722	0.2	-42.1±7.0	-40.7±5.4		
	cotton	7,081,389±561,649	6,973,827±558,719	107,561±4,955	1.5	-57.1±6.1	-32.8±22.9		
	maize	6,132,660±387,500	5,190,108±324,660	975,377±48,666	15.9	-13.2±9.1	-4.7±15.0	-17.7±11.6	-23.0±10.3
	groundnut	6,004,865±541,980	5,987,747±542,482	17,456±2,071	0.3	-13.7±56.7	-12.4±51.9	-20.0±3.2	-39.5±9.3
	rice	5,672,274±602,584	1,841,263±184,051	3,719,550±655,285	65.6	-0.1±28.0	10.5±33.5	-31.5±9.3	-28.6±11.1
	beans	3,594,965±539,054	3,569,138±523,477	29,547±3,771	0.8	0.3±10.7	-19.5±10.0		
	sunflower	1,429,214±75,129	1,422,255±75,539	6,682±410	0.5	16.8±20.4	40.2±50.9	-18.4±4.5	-46.2±2.4
	sugarcane	1,083,650±211,776	1,059,856±201,935	24,118±8,199	2.2	12.0±3.9	79.8±30.8	12.1±2.3	30.2±21.4
	soy	389,584±165,593	336,958±160,751	55,066±3,617	14.1	5.1±23.6	11.0±38.6	-26.5±14.6	-32.9±18.5
	peas	263,621±45,288	255,351±43,661	8,270±1,518	3.1	0.2±2.8	28.6±34.3	-27.3±2.1	-25.8±20.6
	cassava	223,824±79,443	223,789±79,439	30±4	<0.1	1.2±32.8	12.9±61.0	-27.6±2.4	-10.5±4.1
Senegal	All crops	866,137±237,788	865,665±237,598	215±93	<0.1	-10.7±25.9	-29.7±40.9	-28.9±20.3	-43.6±28.3
	groundnut	380,872±118,585	380,872±118,585				-33.9±50.2		-44.1±28.4
	millet	351,747±74,362	351,747±74,362				-19.7±31.9		-34.8±23.2
	sorghum	66,209±15,476	66,208±15,476	1±0	<0.1	-45.2±21.7	-58.6±35.2		
	maize	37,530±20,288	37,471±20,264	59±25	0.2	-20.1±14.2	-24.7±30.5	-27.3±19.9	-34.5±31.3
	cotton	9,923±5,667	9,923±5,667				-46.6±35.4		
	rice	9,414±2,089	9,003±1,924	154±68	1.6	6.4±18.5	-4.0±36.0	-28.1±14.1	-33.8±29.5
	cassava	9,399±1,295	9,397±1,294	2±0	<0.1	3.9±11.8	3.0±64.5	-27.9±11.0	-18.3±69.5
	peas	533±0	533±0				16.3±32.1		-50.0±1.4
	sugarcane	509±26	509±26	<1	<0.1	-14.8±0.0	18.1±51.9	-14.9±0.0	-12.9±51.7
Burkina Faso	All crops	1,132,456±108,566	1,132,262±108,542	194±1	<0.1	-7.7±26.1	-30.6±23.2	-33.1±15.5	-32.7±15.1
	millet	545,646±14,436	545,646±14,436			-13.6±7.1	-21.8±16.2	-12.6±3.0	-32.1±11.6
	sorghum	450,950±65,981	450,950±65,981			-33.6±11.4	-50.9±13.4		
	groundnut	72,380±16,324	72,380±16,324			-10.0±54.8	-37.5±48.8	-26.7±2.9	-61.0±22.6
	maize	44,399±8,000	44,366±8,000	33±1	0.1	-24.2±31.7	-26.4±24.2	-27.5±35.4	-38.9±26.3

Country	Crop	Total Harvest Area	Rainfed Area	Irrigated area	% irrigated area	Irrigated Yield CC	Rainfed Yield CC	Irrigated Yield CC w/o CO2	Rainfed Yield CC w/o CO2
	cotton	13,022±2,879	13,022±2,879				-48.5±16.1		
	rice	6,042±945	5,881±922	161±0	2.7	-7.4±26.2	-11.4±30.7	-34.1±12.9	-46.8±25.2
	sugarcane	18±0	18±0	<1	0.3	-28.1±5.1	43.8±29.1	-27.9±5.2	18.2±35.7
Kenya	All crops	915,591±110,775	915,154±109,787	461±138	0.1	-11.5±17.2	3.1±38.8	-13.0±14.7	-13.2±28.6
	maize	479,083±60,362	478,653±59,378	453±137	0.1	-11.5±18.2	4.1±33.3	-15.2±17.0	-12.8±27.7
	beans	249,453±31,634	249,453±31,634				-2.1±20.8		
	sorghum	62,632±4,558	62,632±4,558				-23.7±16.8		
	wheat	44,589±5,374	44,589±5,374				-8.1±74.9		-50.3±28.8
	millet	37,501±3,181	37,501±3,181				1.4±12.5		-15.9±6.7
	cassava	14,924±2,082	14,924±2,082				57.1±119.7		22.2±34.2
	sugarcane	11,368±1,814	11,368±1,814				90.9±45.1		37.7±32.8
	cotton	8,336±1,405	8,329±1,401	7±0	0.1	-44.4±11.9	-35.9±14.5		
	groundnut	7,270±190	7,270±190				-4.6±52.7		-24.5±8.6
	sunflower	197±89	197±89				35.2±31.0		-46.4±28.5
	rice	162±86	162±86				28.8±37.5		-18.5±30.0
	peas	76±0	76±0				36.9±34.6		-21.2±15.0
Tanzania	All crops	76,980±28,876	76,943±22,770	36±54	<0.1	-8.8±8.0	-7.5±22.1	-14.2±8.2	-16.4±19.9
	maize	28,611±20,598	28,576±14,833	35±52	0.1	-9.1±15.9	-8.4±24.7	-13.5±19.0	-11.9±17.4
	sorghum	20,390±562	20,390±562				1.6±15.8		
	millet	19,257±696	19,257±696				4.1±32.7		-21.3±8.8
	cotton	3,321±2134	33,20±2076	2±2	<0.1	-37.1±0.8	-12.1±18.6		
	wheat	1,895±970	1,895±970				-2.3±41.7		-32.4±23.1
	cassava	1,389±1153	1,389±1153				54.2±49.9		5.5±9.7
	rice	813±1205	813±922	<1	<0.1	8.8±10.5	6.8±17.8	-11.0±9.8	-17.0±13.6
	groundnut	750±735	750±735				-13.9±29.5		-32.4±1.9
	sunflower	287±425	287±425				19.1±16.4		-25.2±6.2
	peas	136±201	136±201				17.1±10.3		-26.8±7.0
	beans	132±196	132±196				15.4±1.0		
Pakistan	All crops	4,144,983±374,838	2,311,831±148,913	1,824,197±104,325	44	-9.6±26.7	-3.1±48.3	-36.6±20.9	-34.5±22.9
	wheat	2,110,746±197,844	764,742±25,711	1,343,094±72,427	63.6	-8.8±25.3	-2.7±34.3	-32.5±16.5	-37.4±19.4
	cotton	677,732±56,949	659,880±55,209	17,852±1,346	2.6	-70.3±7.2	-45.4±42.4		

Country	Crop	Total Harvest Area	Rainfed Area	Irrigated area	% irrigated area	Irrigated Yield CC	Rainfed Yield CC	Irrigated Yield CC w/o CO2	Rainfed Yield CC w/o CO2
	rice	485,847±58,042	163,118±5,987	323,431±23,954	66.6	-3.2±60.0	-1.9±70.3	-55.1±24.6	-44.8±19.8
	maize	318,113±10,117	183,630±11,400	127,660±5,943	40.1	-42.5±39.5	-3.5±54.4	-45.5±44.1	-26.9±44.3
	sugarcane	238,148±15,835	233,222±15,741	4,926±349	2.1	18.9±7.9	128.8±37.0	19.1±8.2	69.5±14.7
	millet	94,487±7,577	93,849±7,584	643±14	0.7	-19.7±16.6	0.3±45.0	-10.3±3.0	-19.6±30.8
	sorghum	76,681±9,608	75,397±9,358	1295±74	1.7	-59.8±21.2	-50.0±23.9		
	beans	61,800±9,840	59,182±9,368	2648±110	4.3	-24.1±11.0	-13.9±17.7		
	groundnut	30,010±1,719	30,010±1,719				19.1±129.3		-45.3±30.9
	peas	26,783±3,876	24,167±3,404	2646±108	9.9	4.8±6.6	10.0±18.7	-19.9±8.2	-30.4±20.2
	sunflower	24,635±3,432	24,634±3,432	1±0	<0.1	7.7±18.1	74.6±123.5	-20.6±1.4	-31.0±6.3
Tajikistan	All crops	176,497±15,295	130,123±11,693	44,274±1,091	25.1	2.3±29.7	10.9±57.5	-19.1±23.6	-13.2±23.6
	wheat	99,138±9,004	62,627±5,877	34,665±725	35	6.5±32.0	17.6±45.1	-17.3±23.4	-14.2±20.5
	cotton	68,527±5,752	63,815±5,547	4,574±205	6.7	-66.5±8.9	-45.1±5.9		
	rice	4,825±276	1,592±106	3,161±117	65.5	-6.6±31.3	88.3±78.5	-36.7±19.3	-27.9±41.5
	maize	3,062±181	1,302±83	1,715±33	56	-7.1±26.9	72.5±72.6	-15.0±22.0	3.6±19.8
	peas	583±82	431±80	152±11	26.1	10.7±3.1	63.7±10.8	-19.6±3.9	-16.3±25.9
	sunflower	239±0	232±0	6±0	2.7	11.1±8.6	194.2±277.7	-23.4±4.5	-12.9±10.5
	millet	102±0	102±0				81.1±136.8		84.7±99.2
	groundnut	15±0	15±0				22.6±105.0		-22.7±9.1
	sorghum	7±0	6±0	1±0	16.3	-53.9±7.1	-25.4±23.7		

Note: Results include rainfed and irrigated yield, with and without CO_2 effects. Median values are reported (%); the range represents spread in the results across all GCM-GGCM simulations. Total harvested, irrigated and rainfed areas are reported (ha) for the semi-arid areas exclusively.

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