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Climate change impacts and adaptation strategies: an assessment on sorghum for Burkina Faso

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Abstract

Adaptation strategies sustaining agricultural production under climate change are urgently required in Sub-Saharan Africa. To quantify the impacts of different adaptation options in Burkina Faso, this study simulated sorghum yields under current and projected climatic conditions with and without adaptation. We used the Decision Support System for Agrotechnology Transfer (DSSAT) at 0.5° spatial resolution (around 55 km) and forced the model with two climate change scenarios. Our calibrated model showed good agreement between reported and simulated yields (Pearson's r = 0.77; out-of-sample r = 0.68). DSSAT was configured to mimic four distinct adaptation measures: integrated soil fertility management (ISFM), irrigation, an improved variety, and agroforestry. Results show that nationally averaged sorghum yields are projected to decrease by 5.5% under high emissions by 2090 without adaptation. Major yield losses (up to 35%) would occur in the southern and western parts of the country. Our assessments identify ISFM as the most effective adaptation strategy, increasing yield up to 300%, followed by agroforestry (up to 125%), an improved variety (up to 90%), and irrigation (up to 43%) at the regional scale. ISFM is effective across all regions, while irrigation and an improved variety are most effective in the northern and western parts. Agroforestry, meanwhile, is most effective in the south and eastern part of the country. We conclude that climate change in Burkina Faso could negatively affect sorghum yields, but adequate adaptation options exist to enhance agricultural resilience.

Keywords: *DSSAT, Spatial modeling, Sahel, Impact assessment, Adaptation measures, Agricultural resilience.*

1. Introduction

One of the biggest challenges of the 21st century is climate change, which affects the livelihoods and natural resources of the planet. Studies project a decline in agricultural production in Sub-Saharan Africa (SSA) by 2080, and this is particularly severe in Sahelian countries . Agriculture in the Sahelian region is dominated by millet, sorghum, peanut, and cowpea, grown in annual rotations or intercropped. Sahelian countries are currently net importers of cereals, indicating that the current production is insufficient to meet domestic demands (FAOSTAT, 2022). The existing trends in Sahelian agriculture indicate that shortages are expected even without the adverse effects of climate change (Gerland et al., 2014; Ray et al., 2013). Additionally, ecosystems in SSA are already being affected by climate change, and future impacts are expected to aggravate the vulnerability of agricultural systems, particularly in semi-arid areas (Bunclark et al., 2018).

For Burkina Faso, studies project a continuous and significant warming trend until the end of the century above the global mean. Future precipitation is subject to modeling uncertainties which could lead to wetter or dryer conditions in the Sahel (Sylla et al., 2016; Traore and Owiyo, 2013). Agriculture is the most climate-dependent human activity (Torquebiau, 2017). Given the impacts of climate change on agriculture, suitable adaptation measures should increase or stabilize yield (Sapkota et al., 2018). Thus, agricultural production must be intensified through efficient farm management practices to withstand climate change, especially in vulnerable regions like the Sahel. Climate change impact assessments should inform the development of appropriate responses in space and time as impacts and adaptation responses vary across regions (Douxchamps et al., 2016). Suitable adaptation strategies should consider mitigation benefits, stakeholder interests, and institutional settings.

Burkina Faso's farmers have a long history of adapting their farming strategies to local climate conditions (Alvar-Beltrán et al., 2020; Sorgho et al., 2020). They rely mainly on a short single rainy season for crop production as the source for their income generation, food security, and dietary requirements of their households (Myers et al., 2017; Zougmoré et al., 2014). The majority of these smallholder farmers have low ability and capacity for adaptation (Callo-Concha, 2018). However, few communities reported successfully adopting resource-conserving techniques such as water harvesting, which has improved land degradation and household food security (Bossio et al., 2008; Noble et al., 2008; Pretty et al., 2006). For effective adaptation policies, understanding climate change impacts, regionally differing agricultural systems, and adaptation strategies are essential (Sorgho et al., 2020). Our study focused on providing quantitative impact assessments of adaptation strategies in sorghum, the further impetus for policy and technology adoption.

In recent times, a considerable amount of studies have been conducted assessing the impacts of climate change through various modeling approaches, including statistical and biophysical modeling worldwide (Aryal et al., 2020; Harvey et al., 2018; Kogo et al., 2021; Ray et al., 2019; Schleussner et al., 2018; Sultan et al., 2019; van Oort and Zwart, 2018). A few studies based on statistical modeling report a negative impact on cereal production with increasing temperature in Burkina Faso (Belesova et al., 2019; Nana, 2019; Sossou et al., 2020), additionally causing economic loss (Henderson et al., 2018). However, there is a limitation in quantifying the impacts of climate change and adaptation measures by considering agronomic practices (biophysical modeling) and soil properties in addition to climate information spatially at the national level (at grid scale) in Burkina Faso.

In this study, we used the biophysical process-based model Decision Support System for Agrotechnology Transfer (DSSAT) to assess the impacts of climate change on sorghum yields. In Burkina Faso, sorghum is the primary cereal crop, covering about 1.9 million hectares for a production of about 1.85 million tons during the 2019-2020 agricultural season (DGESS/MAAH, 2020). Millet and sorghum are the two primary crops for rural inhabitants, although yields have persistently remained below global average sorghum yields despite numerous varietal breeding programs (vom Brocke et al., 2020). We evaluated the ability of four adaptation strategies (integrated soil fertility management (ISFM), irrigation, an improved variety, and agroforestry) to buffer climate change-induced yield losses. We applied the model calibrated on local yield records to provide a spatial assessment of climate change impacts and adaptation responses. This study aimed to simulate sorghum yields in Burkina Faso under current and projected climatic conditions and different adaptation strategies. This information is needed to develop National Adaptation Plans (NAP) and Nationally Determined Contributions (NDC) investment plans for agricultural policy planning, extension officers, and farmer's organizations to anticipate impacts and select the best climate change response strategies.

2. Material and Methods

2.1. Overview of impact assessment methodology

We followed the steps shown in Figure 1 to assess the impacts of climate change and adaptation strategies in Burkina Faso. The first step was to calibrate the model to match simulated and reported sorghum yields for the years 2001-2016, using the observed current climate data (information on climate data is found in section 2.3). Second, the calibrated model was used to simulate sorghum yields under different scenarios, different management practices (with or without adaptation), different time periods (current and three future slices – 2021-2040, 2041-2060, 2081-2100), and the two emissions scenarios. In the third step, this multi-dimensional comparison allows for deducing viable adaptation strategies under climate change. All simulations were conducted at a 0.5°x0.5° spatial grid level (approx. 55x55 km²). We averaged annual yields for all bi-decadal time slices to smoothen annual variations in weather.

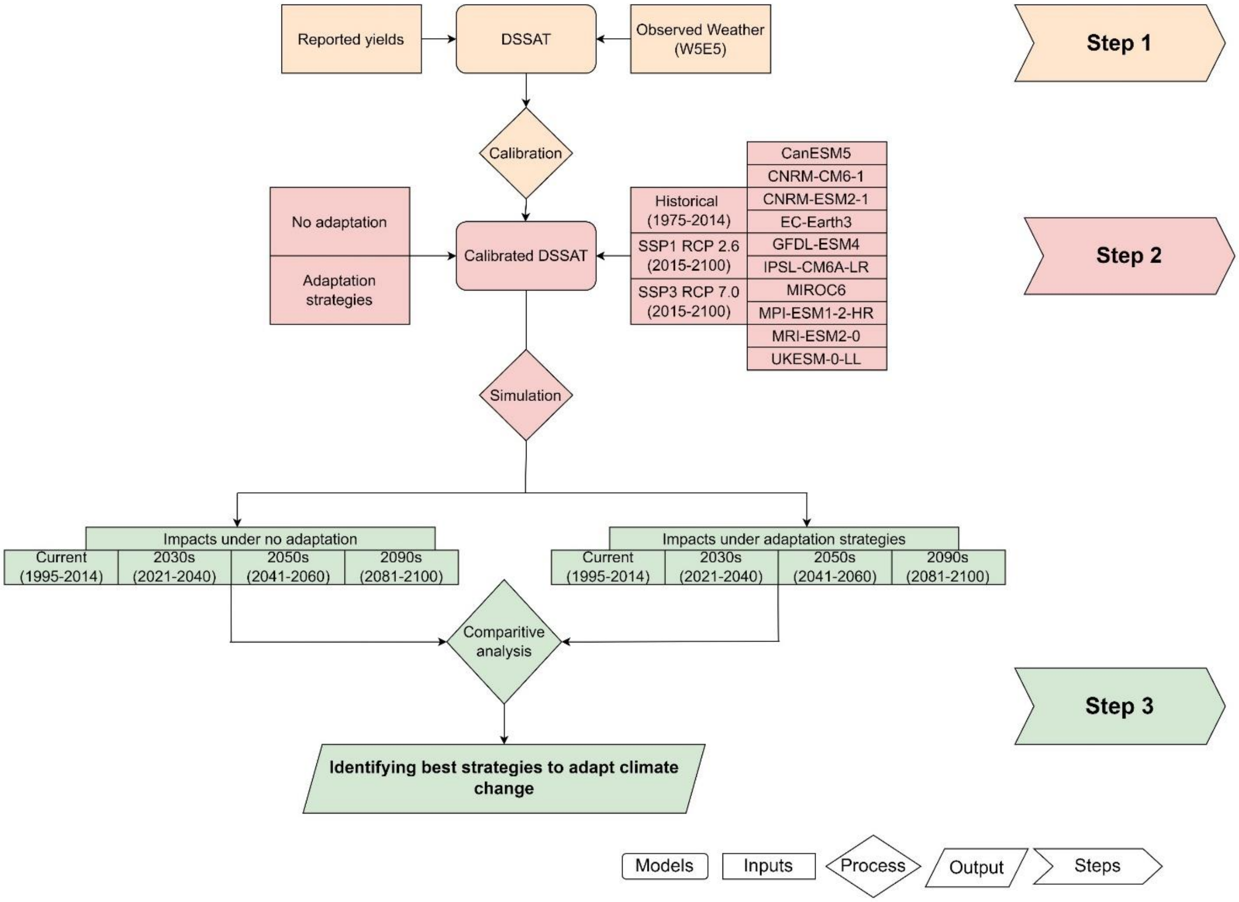

Figure 1: Methodology flowchart to assess the impacts of climate change and adaptation strategies on sorghum yields in Burkina Faso. The usage of symbols is explained in the legend at the bottom.

2.2. Study Area

Burkina Faso is located in the Sahel and Savana zone, with a semi-arid climate in the North and a sub-humid climate in the South. It is highly vulnerable to climate change due to a combination of weather variability, dependency on rain-fed agriculture, and limited economic and institutional capacity to cope with and adapt to climate change (Challinor et al., 2007; Müller et al., 2010; Roudier et al., 2011). Figure 2 shows the regional boundaries of the study area with their crop area fraction (Buchhorn et al., 2020) and simulation grids at 0.5°x0.5° spatial resolution.

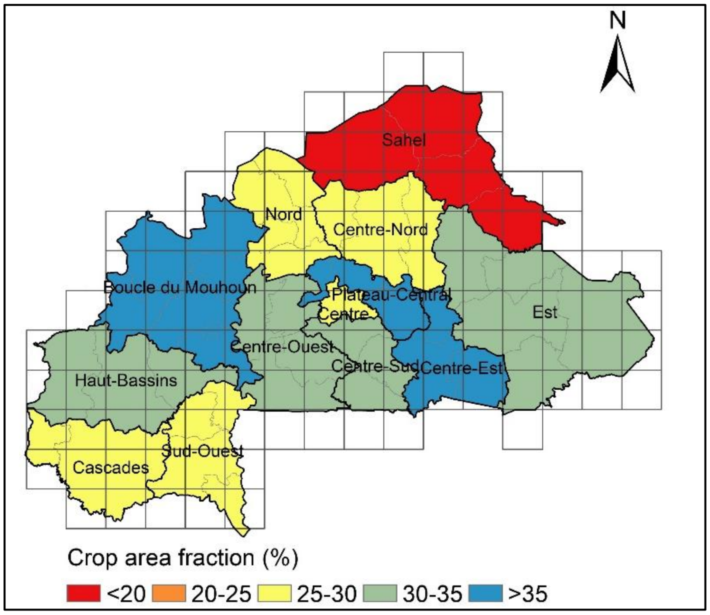

Figure 2: Regional boundaries of Burkina Faso with their crop density (Buchhorn et al., 2020) and grids (0.5° X 0.5°) for simulation.

2.3. Climate data, emissions scenarios, and climate indicators

The basis for evaluating the current climate and past climate changes in this study is the W5E5 data set (Cucchi et al., 2020; Lange et al., 2021), which integrates simulations from global weather models, satellite observations, and weather station observations. The dataset covers the period 1979-2016 at daily temporal resolution and the entire globe at 0.5°x0.5° grid spacing (in Burkina Faso, approximately 55km x 55km). For calculating past trends, the time periods 1997-2016 (short-form: 2006) and 1979-1998 (short-form: 1988) are compared with each other. W5E5 was compiled to support climate bias adjustment of those climate models (General Circulation Models, GCMs) used in phase 3b of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) (Lange, 2021, 2019). Future climate projection data simulated by GCMs was obtained from ISIMIP3b, which compiles a set of 10 GCMs based on bias-adjusted and downscaled CMIP6 data. Historical simulations of ISIMIP3b cover 1850-2014, and future projections cover 2015-2100 at daily temporal resolution at 0.5° x 0.5° spatial grid.

This study focused on the scenarios SSP1-RCP2.6 and SSP3-RCP7.0, used in the 6th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) to assess a wide range of possible future socio-economic and emissions scenarios (Arias et al., 2021). The scenario SSP1-RCP2.6 pictures a sustainable future where global warming is likely to be well below 2°C and thus in line with the Paris Agreement. Meanwhile, the scenario SSP3-RCP7.0 depicts high challenges for mitigation and adaptation in a world with no or little climate policy interventions (Hausfather, 2018). The analysis focuses on the periods 1995-2014 (short: 2004) as the reference period and the three future periods 2021-2040 (short: 2030), 2041-2060 (short: 2050), and 2081-2100 (short-form: 2090). The GCMs included in ISIMIP3b are: CanESM5 (short-form: Can), CNRM-ESM2-1 (short-form: CNES), CNRM-CM6-1 (short-form: CNCM), EC-Earth3 (short-form: EC), GFDL-ESM4 (short-form: GFDL), IPSL-CM6A-LR (short-form: IPSL), MIROC6 (short-form: MIROC), MPI-ESM1-2-HR (short-form: MPI), MRI-ESM2-0 (short-form: MRI) and UKESM1-0-LL (short-form: UKE) (Lange, 2021, 2019). GCMs naturally show different projections due to inherent insufficiencies in modeling the climate. Different projections indicate the range of modeling uncertainty, and the multi-model ensemble median (MMEM) provides a conservative estimate of possible climate changes. Thus, the MMEM is shown additionally to the individual model results.

To analyze past and future climate changes, the indicators analyzed in this study are the annual average mean air temperature, the number of very hot days per year (maximum temperature above 35°C), the number of very hot nights or tropical nights per year (minimum temperature above 25°C), the mean annual precipitation, the heavy precipitation intensity, the rainy season onset as well as year-to-year variability of mean annual precipitation (calculated based on the standard deviation). The indicator for heavy precipitation intensity is the maximum daily precipitation of a year. Rainy season onset was obtained using a definition adapted from (Laux et al., 2008) and (Stern et al., 1981), designed for West Africa. Rainy season onset is thus considered to be the first day of the year on which the following three conditions are simultaneously met: a) At least 20mm rainfall within five days, b) The starting day and at least two other days in these five days are wet (≥ 0.1 mm rainfall) and c) No dry period of seven or more consecutive days within the next 30 days.

2.4. Crop model and its inputs

Crop yield is a function of weather and other field inputs such as soil and farmers' practices. This can be formed as equations representing a crop's physiological response to environmental variables (Jones et al., 2003). Biophysical crop simulation models simultaneously incorporate interacting soil, plant, field inputs, and weather information. In this study, we used DSSAT (Hoogenboom et al., 2019, 2017; Jones et al., 2003), a widely used process-based crop model that simulates crop growth as a function of soil-plant-atmosphere dynamics. The model requires daily weather data, soil surface and profile information, detailed crop management information, and genetic coefficients of the planted variety as inputs. DSSAT calculates plant and soil water, nitrogen, phosphorus, and carbon balances, as well as the vegetative and reproductive development of crops at a daily temporal interval.

We used DSSAT's default West African sorghum variety (Table A.1) for calibration to simulate sorghum yields under rainfed and no-fertilizer conditions for the following two reasons. First, the water-unlimited yield potential seems a more sensible reference to calculate yield gaps than the yield potential determined by rainfed farming systems in SSA (Tittonell and Giller, 2013). Second, many smallholder farmers can hardly afford the recommended quantities of fertilizers in SSA (Rurinda et al., 2020) – which is reflected by lower nutrient application rates in SSA, averaging at only about 16 kg per hectare^{-1} and year^{-1}, compared to over 100 kg in Europe and North America, and over 150 kg in China (IFASTAT, 2018). The model automatically calculates the sowing date when the field meets at least 10% of soil moisture, and the temperature reaches between 10-40°C between Julian Days 125 to 160. Similarly, harvest dates are automatically calculated by DSSAT when the crop has reached maturity. Planting depth was set to 3 cm, row spacing to 45 cm, and plant density to 13 plants/m² (White et al., 2015). We used ISIMIP3b CO_2 concentration data (Lange, 2019) for the future and the model-inherent default for the current period (380 ppm). These simulations were conducted for the future (2015 -2099) under SSP1-RCP2.6 and SSP3-RCP7.0 scenarios. We rely on yield statistics provided by the Ministry of Agriculture in Burkina Faso for model calibration (MAAH/DGESS, 2020). For soil profiles, we used the HC27 Generic Soil Profile Database. This database consists of 27 generic soil profiles (Koo and Dimes, 2013) based on three criteria: texture, rooting depth, and organic carbon content. Three levels for each category (texture, rooting depth, and organic carbon content) were classified using the boundary conditions based on the meta-analysis of WISE 1.1 soil profiles measured at cropland areas in Sub-Saharan Africa.

2.5. Model Calibration

Model calibration is necessary to prepare the model for accurate simulations, matching yield observations with simulations by adjusting input parameters in the model. Deriving location-specific crop genetic coefficients is a common practice in calibration (Jones et al., 2015). However, given the lack of field or grid-level observations that would be necessary for this, we resorted to hypothetical trials (Li et al., 2018) to calibrate DSSAT with national average yields (Table 1). We used the Generalized Likelihood Uncertainty Estimation (GLUE) (He et al., 2010, 2009) to derive optimal crop genetic coefficients of the variety. We calibrated the default variety of the model “W.AFRICAN” to match the national average yield level of 990 kg/ha. GLUE is a Bayesian estimation method that uses Monte Carlo sampling from prior distributions of the coefficients and a Gaussian likelihood function to determine the best coefficients based on the experiments that are used in the estimation process. We conducted the following steps to calibrate genetic coefficients.

- First, we created an array of experiments (Table 1) with the national average yield (990 kg/ha), assumed sowing dates (Julian Day: 125-135), anthesis dates (Julian Day: 160-170), and maturity dates (Julian Day: 200-210) for the years 2001-2015, deliberately omitting 2016 for later validation. GLUE is designed for calibration, specifically for field trials with observed data such as sowing date, anthesis date, maturity date, productivity, etc. We adapted and implemented this tool at the spatial level. Therefore, we crafted hypothetical field trials for each grid cell. As there is a lack of observations from the field, we assumed three different trials (Table 1) for calibration.
- Second, we simulated yields with grid-specific soil, weather, and management options via GLUE until they reached a level closest to the reported mean (2001-2015) yield (990 kg/ha) for each grid cell. During this process, GLUE tests and generates new genetic coefficients from the default variety of W.AFRICAN to match reported yields.
- Finally, we averaged the generated genetic coefficients from all grids to derive the final (hypothetical) sorghum variety. We calibrated the genetic coefficients P1, P2R, P5, and G2 (Table A.1). Genetic coefficients of the default variety and the calibrated variety are given in Table A.1.

Table 1: An array of assumed experiments to derive genetic coefficients

Sowing date (Julian Days)	Anthesis Date (Julian Days)	Maturity Date (Julian Days)	Harvested Yield (kg/ha)
125	160	200	990
130	165	205	990
135	170	210	990

We used the national level yields for all grids instead of regional or grid cell-specific yields because treatments that are being used for model calibration should not be exposed to any water or nutrient stress and pests, weeds, and diseases – but yields in the Sahel region are frequently exposed to water stress. Moreover, we aimed to generate one national-level variety instead of developing region-specific varieties.

2.6. Adaptation strategies

We implemented four different farming adaptation strategies in the model to assess yield impacts for current and future climates.

- First, **Integrated Soil Fertility Management (ISFM)**, locally known as **Zaï** practice, is a local technology that combines rainwater collection and nutrient management in West Africa (Fatondji et al., 2011; Roose et al., 1993). It promotes crop production on degraded soil and eases the adverse effects of dry spells, which are frequent during the Sahel region's cropping period (Fatondji et al., 2006; Hassan, A., 1996; Roose et al., 1993). Zaï or other soil and water conservation techniques for crop production could increase crop production and food security in West Africa's drylands. Since this adaptation strategy is not directly available as an option in DSSAT, we set initial soil conditions in DSSAT by keeping water availability at 60% and nitrogen content at 62 kg/ha (Fatondji et al., 2012; Faye et al., 2018). This is because Zaï could increase the soil water content and water and nutrient use efficiency by trapping water and enhancing its retention and infiltration into the soil for uptake by plants (Dougbedji, 2002; Kebenei et al., 2021).
- Second, we considered adaptation by **irrigation**, which reportedly positively impacts production, farm incomes, employment, consumption, food security, and non-farm businesses (Akudugu et al., 2021). To enable irrigation as an adaptation strategy in the model, we used the option "automatic irrigation when required," i.e., not considering the actual availability of water resources. We set the irrigation flood depth at 5cm when the crop requires water.
- The third adaptation strategy consists of an **improved variety**, which might help to improve the resilience of food production in the region (Akinseye et al., 2017). Improved sorghum variety was chosen based on their selection history, phenology (maturity and photoperiod sensitivity), and grain yield productivity to represent contrasting sorghum types cultivated in West Africa (Adam et al., 2018). In this study, we used Fadda, a single-cross hybrid with Guinea-race-derived parents, and grain yield productivity exceeded that of farmers' local varieties by up to 600kg/ha, corresponding to an increase of approx. 60% (Rattunde et al., 2016).
- The fourth and final adaptation option is the implementation of **agroforestry**. It can increase Soil Organic Carbon (SOC) and nitrogen content by up to 20% by photosynthetic fixation of carbon from the atmosphere and by transferring it to the soil (Kuyah et al., 2019). In some cases, it can contribute to a surplus profit when harvesting tree products (Bado et al., 2021). However, modeling tree-crop interactions is currently not available in DSSAT. Thus, the effects of agroforestry on soil properties were added to the model by increasing SOC and soil nitrogen content by 20% based on a meta-analysis (Kuyah et al., 2019). This meta-analysis indicates that agroforestry systems in Sub-Saharan Africa can increase crop yields while maintaining and regulating soil properties.

2.7. Model evaluation

Simulated yields (2001 to 2015) using W5E5 climate data were aggregated to the national level to compare them with observed yields (2001 to 2015) for assessing the simulation ability with the nationally average variety. An additional out-of-sample validation for the year 2016 – which was not used for calibration – was performed, comparing simulated and reported yields on the sub-national (regional) level. The correlation coefficient (*r*) and the Index of Agreement (d) are standard performance measures and were used for assessing the goodness of fit. While *r* calculates how much correlation there is between observed and simulated anomalies, the Index of Agreement (d) indicates the degree of model prediction error with values between 0 (no agreement) and 1 (perfect match).

3. Results

3.1. Past and future climate in Burkina Faso

To identify changes in future climatic conditions in Burkina Faso, we analyzed several indicators concerning projected temperature and precipitation under the two emissions scenarios based on continuously high greenhouse gas emissions (SSP3-RCP7.0) and solid climate mitigation (SSP1-RCP2.6) for 2030, 2050, and 2090. Figure A.1 shows the current mean annual temperature and precipitation. It indicates that southern Burkina Faso has a lower mean annual temperature and higher rainfall than the northern part.

3.1.1. Past and future precipitation trends

Burkina Faso experienced decades of drought in the 1970s and 1980s. Mean annual precipitation has partially recovered since then but has not yet returned to its pre-1970s values (based on analysis with CRU data). Annual precipitation amounts have increased since the 1980s in almost all parts of Burkina Faso by up to 150 mm (Figure 3a). In continuation of this existing trend, the MMEM projects future increases in annual precipitation sums in the whole country under the high emissions scenario. Under the low emissions scenario, almost no changes are projected for the next decades. The projections show a large spread between models, especially under the high emissions scenario (Figure 4).

Heavy precipitation intensity has augmented in the last decades in almost all parts of the country compared to current values (Figure 3b). Furthermore, heavy precipitation intensity is projected to increase in all parts of the country under high emissions (Figure A.2), similar to the projected increase of the mean annual precipitation sum (Figure A.3). Under the high emissions scenario, all models agree on an increasing trend in heavy precipitation intensity. Under the low emissions scenario, the models project no or small increases in heavy precipitation intensity until the end of this century. Rainy season onset and length showed high variability but no clear trend over Burkina Faso in recent decades (Figure 3c). For the future, the climate models tend to project a later start of the rainy season under SSP1-RCP2.6 and no clear trend under SSP3-RCP7.0 with regional differences and changes over time (Figure A.4).

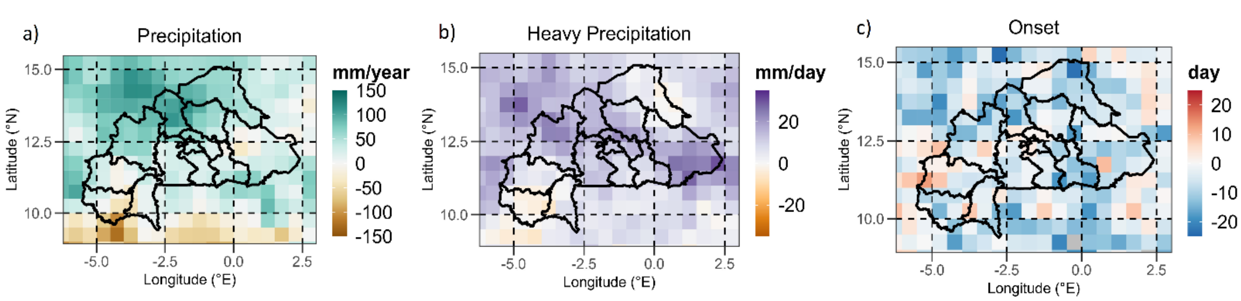

Figure 3: Changes in mean annual precipitation (left), heavy precipitation events (center), and the onset of the rainy season (right) between the periods 1997-2016 and 1979-1998 (i.e., mean of the later time slice minus the mean of the previous).

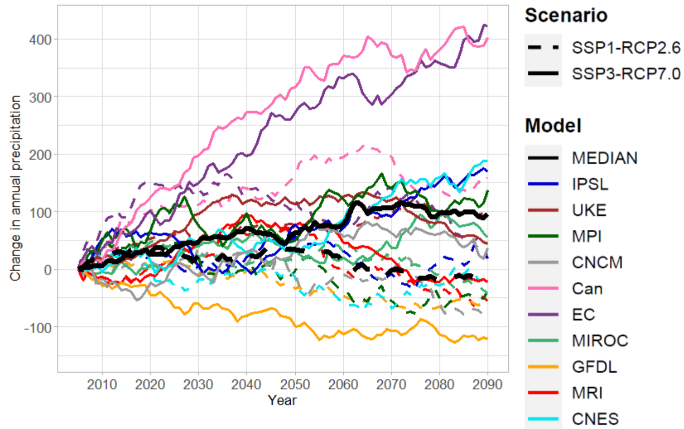

Figure 4: 11-year running mean of change in mean annual precipitation in mm compared to 2004. Values are averages over Burkina Faso. Each variegated line indicates a projection of one of the 10 individual models. The black line displays the MMEM.

3.1.2. Past and future temperature trends

In recent years, mean annual temperatures showed a rise of 0.15°C per decade (1997-2016 (2006s) compared to 1979-1998 (1988s) over Burkina Faso (Figure A.5- left). For the future, climate models project a robust trend toward increasing temperatures in Burkina Faso over the 21st century. This is evident in both analyzed scenarios, albeit to different degrees. The MMEM indicates an average increase of mean annual temperature over Burkina Faso of 0.6°C (2030), 0. 9°C (2050) to 1.1°C (2090) under SSP1-RCP2.6 (low emissions scenario) and of 0.5°C (2030), 1.3°C (2050) to 3.6°C (2090) under SSP3-RCP7.0 (high emissions scenario) in reference to 2004. Under the low emissions scenario, temperatures do not increase strongly after 2050, following the stabilization of GHG emissions before mid-century. Temperature projections show very high confidence, with all models showing the same trend (Figure A.6). Even though the models show different magnitudes of temperature increases under the high emissions scenario, they all show a continuous increase until 2090.

Consistent with the recent temperature increases, the number of temperature extremes, namely tropical nights and very hot days, also soared (Figure A.5– center and right). In the future, the number of very hot days and tropical nights is projected to increase in all parts of the country and under both emissions scenarios, reaching values of 270 tropical nights per year (Figure A.7) and 308 very hot days (Figure A.8) in Burkina Faso at the end of this century under the high emissions scenario.

3.2. Model calibration and out-of-sample validation

To investigate the simulation capability of the calibrated model, we analyzed the inter-annual variability of yields from 2001 to 2015 (Figure 5a) at the national scale and an out-of-sample validation at the regional scale yields for the year 2016 (Figure 5b), which was not used in the calibration. The model captures both the dynamics and the amplitudes of national average yields (r = 0.77 and d = 0.85) against observed yields in most years on the national scale. The out-of-sample validation on the regional level in 2016 shows a good agreement (*r* = 0.68 and d = 0.81) between observed and simulated yields.

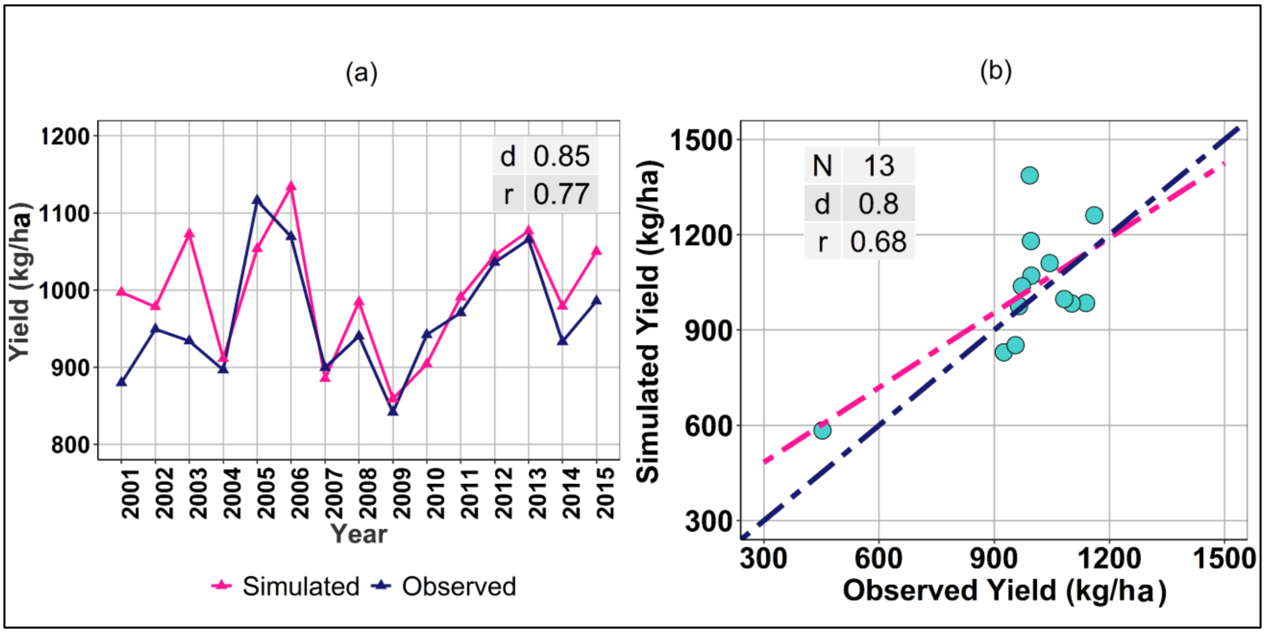

Figure 5: a) Inter-annual variability analysis between observed and simulated yields at the national scale; the indicators d and r represent the index of agreement and Pearson's correlation coefficient, respectively. b) Out-of-sample validation for 2016 at the regional level, displaying the agreement between observed and simulated yields. The pink and blue lines represent the slope and, for comparison, the 1:1 line, respectively. The indicators N, d, and r represent the number of observations, the index of agreement, and Pearson's correlation coefficient, respectively.

3.3. Yield projections under future climate conditions

We simulated sorghum yields under current (1995-2014) and future climate projections from ISIMP3b. Figure 6 shows the current distribution of absolute yield levels in Burkina Faso in 2005 (1995-2014) (left column), together with projected future absolute yields for 2030, 2050, and 2090 under SSP1-RCP2.6 (upper row) and SSP3-RCP7.0 (lower row). Yield projections until 2090 show regionally distinct trends in both scenarios. At the national level, future yields are projected to remain nearly stable under SSP1-RCP2.6, with projected yields of 893 kg/ha in 2030, 892 kg/ha in 2050, and 892 kg/ha in 2090 compared to a yield of 906 kg/ha simulated for the current (2005) period. Under SSP3-RCP7.0, nationally averaged yields are projected to decrease to 857 kg/ha (-5.5%) until 2090 in comparison to the current yields. However, yields are projected to increase slightly (3.6%) in 2030 (940 kg/ha) and to stay nearly the same in 2050 (900 kg/ha). All grid cell-specific results (in the figures) are based on the multi-model mean. The national averages are aggregated from grid cells with weighting by crop area.

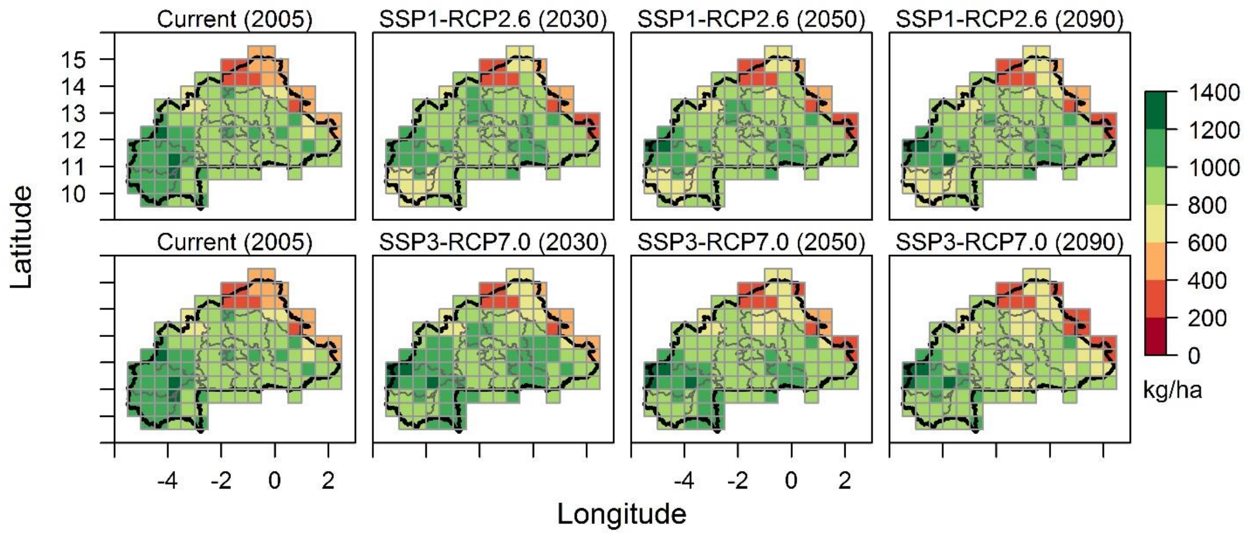

Figure 6: Current and projected future absolute sorghum yield levels (kg/ha) in Burkina Faso at 0.5° grid spacing under SSP1-RCP2.6 (top row) and SSP3-RCP7.0 (bottom row) for years 2005 ("current"), 2030, 2050, and 2090.

The regionally distinct development of yield anomalies under climate change becomes evident in Figure A.9. Until the end of the century, yields are projected to remain nearly unchanged on the national scale. However, at the regional level, yields are projected with partly opposing trends, down to -30% under SSP1-RCP2.6 and up to +20% under SSP3-RCP7.0. Few regions in the north (Sahel, Nord, and Centre Nord) show increased yields (up to +30% under SSP1-RCP2.6 and up to +20% under SSP3-RCP7.0), while few regions in the south (Cascades, Haut-Bassins, and Sud-Ouest) present decreased yields (down to -30% under SSP1-RCP2.6 and down to -20% under SSP3-RCP7.0). Comparing both scenarios, crop yield trends in some regions are more pronounced under SSP1-RCP2.6 than SSP3-RCP7.0. The low emissions scenario SSP1-RCP2.6 results in similar yield impacts in most regions over time. At the same time, for some regions, SSP1-RCP2.6 may lead to stronger yield losses than SSP3-RCP7.0.

3.4. Impacts of adaptation strategies

3.4.1. Integrated Soil Fertility Management (ISFM)

ISFM can almost triple yields, on average, under both emissions scenarios. Comparing both emissions scenarios, under SSP1-RCP2.6, higher yields are projected than under SSP3-RCP7.0 for all time steps (Figure 7). Under SSP1-RCP2.6, the spatial pattern of yields is nearly unchanged over time in the future in southern Burkina Faso (Sud-Ouest, Centre-Ouest, Centre, Centre-Sud, and Centre-Est), and yields are decreasing slightly in the Sahel region. Under SSP3-RCP7.0, the spatial distribution of yield amounts declines from north to south over time in the future. Compared to the current period, yields are projected to decline under both future scenarios. In 2090 under the high emissions scenario (SSP3-RCP7.0), yields are projected to be lower than in other scenarios and time steps, especially in the Sahelian region.

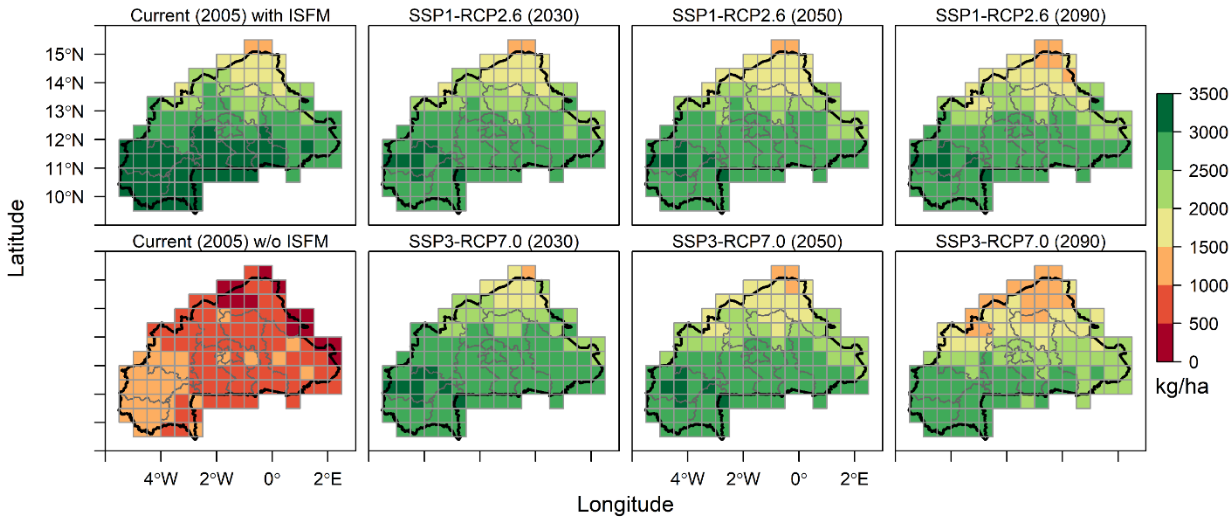

Figure 7: Spatial distribution of yields using ISFM technology for various time steps and scenarios. The top row presents yields for the scenario SSP1-RCP2.6, and the bottom row presents SSP3-RCP7.0. To compare the current with future effects of adaptation, yield distribution maps of the current (2001-2016) with and without adaptation options were given in the left column.

Figure 8 shows the distribution of yield impacts when applying ISFM for different time steps at the national scale. The Y-axis indicates the % difference of yields with and without ISFM intervention for various scenarios and time steps. Under the scenario SSP1-RCP2.6, positive yield impacts (approx. 200%) are projected, while under SSP3-RCP7.0, the positive impact is projected slightly lower and wanes over time than SSP1-RCP2.6. However, under both scenarios, projected yields with ISFM are at least twice as high as current yields without ISFM. Figure A.10 shows the region-specific yield impacts of ISFM under both scenarios and different time steps. Overall, yields increased by up to 300% (at the regional level) with ISFM intervention, especially in the low-yielding regions (Sahel, Est, and Centre-Nord) (Figure A.10).

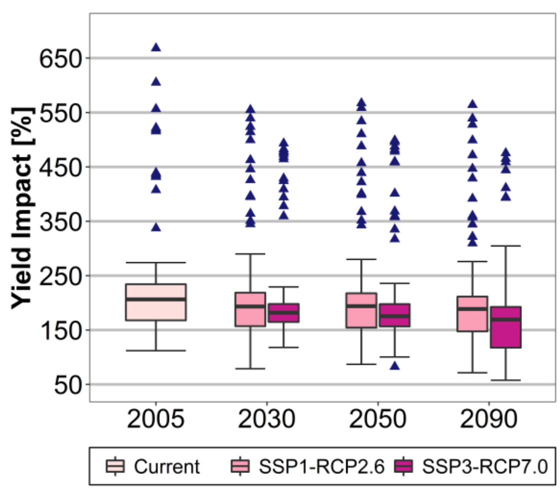

Figure 8: The boxplot presents the grid-wise yield impacts of ISFM over Burkina Faso. The X-axis indicates the time steps, and the Y-axis indicates the % difference of yields with and without ISFM intervention for various scenarios and time steps (i.e., 100% indicates a doubling of the yields). The triangle points represent the outliers. The boxplots show upper, median, and lower values of the yield impact across grid cells.

3.4.2. Irrigation on demand

Overall, irrigation increased yield significantly up to 100% at the grid scale, especially over northern Burkina Faso (Sahel zone) under both emissions scenarios. Comparing both emissions scenarios, under SSP1-RCP2.6, higher yields are projected than under SSP3-RCP7.0 for all the time steps (Figure 9). However, under both scenarios, future yields with irrigation are projected to be lower than the current yields with irrigation. The spatial pattern of projected yield changes under SSP1-RCP2.6 remains nearly unchanged over time, while yields are projected to be declined under SSP3-RCP7.0 over time. Overall, irrigation application shows to have a positive impact on yields under both scenarios, except for a few regions: Cascadas, Haut-Bassins, and Sud-Ouest.

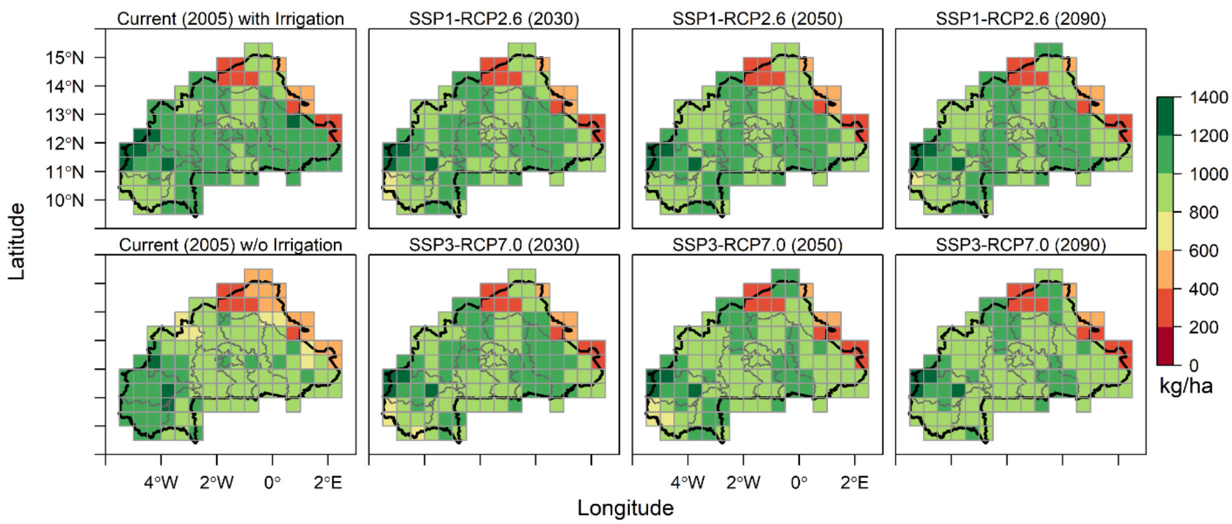

Figure 9: The spatial distribution map of yield using irrigation application for various time-steps and scenarios. The top row presents yields for the scenario SSP1-RCP2.6, and the bottom row presents SSP3-RCP7.0. To compare the current with future effects of adaptation, yield distribution maps of the current (2001-2016) with and without adaptation options were given in the left column.

Figure 10 shows the yield impacts over different time steps with irrigation application at the national level. The Y-axis indicates the % difference of yields between with and without irrigation for various scenarios and time steps. Comparing both scenarios, under the low emissions scenario, yield impacts remain stable over time, but under the high emissions scenario, yields show a slightly increasing trend over time at the national scale. Figure A.11 shows the yield impacts of irrigation for each region under both scenarios and different time steps. Under SSP1-RCP2.6, irrigation leads to higher positive impacts in the southern regions of Burkina Faso (Sud-Ouest, Centre-Ouest, Centre, Centre-Sud, and Centre-Est) than in the northern regions (Centre-Nord, Sahel, and Est) for all time steps. On the contrary, under SSP3-RCP7.0, the positive impacts of irrigation are higher in the north than in the south. Most regions remain unchanged over time under the low emissions scenario (SSP1-RCP2.6) and are interestingly projected to have an increasing trend over time under the high emissions scenario (SSP3-RCP7.0) (Figure A.11).

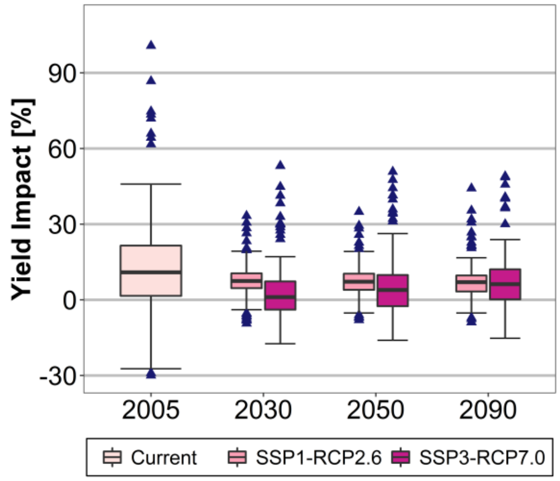

Figure 10: The boxplot presents the grid-wise yield impacts of automatic irrigation over Burkina Faso. The X-axis indicates the time steps, and the Y-axis indicates the % difference of yields between with and without irrigation for various scenarios and time steps (i.e., 100% indicates a doubling of the yields). The triangle points represent the outliers. The boxplots show upper, median, and lower values of the yield impacts.

3.4.3. Improved Variety

Overall, simulations with an improved sorghum variety (Fadda) show increases in yields by up to 150% at grid-scale, especially in the regions Nord, Centre-Nord, and the Sahel region under both emissions scenarios. Figure 11 shows spatial distribution maps of simulated yields with the improved variety adoption for various scenarios and time steps. Under both scenarios (with the improved variety adoption), southern Burkina Faso (regions Sud-Ouest, Centre-Ouest, Centre-Sud, and Centre-Est) is projected to have slightly reduced yields compared with the current (2001-2016) level. Still, few grids from Centre-Nord and Sahel regions are projected to have higher yields. Center regions such as Centre-Sud, Plateau-Central, and Centre are projected to remain nearly unchanged under both scenarios when compared to the current period.

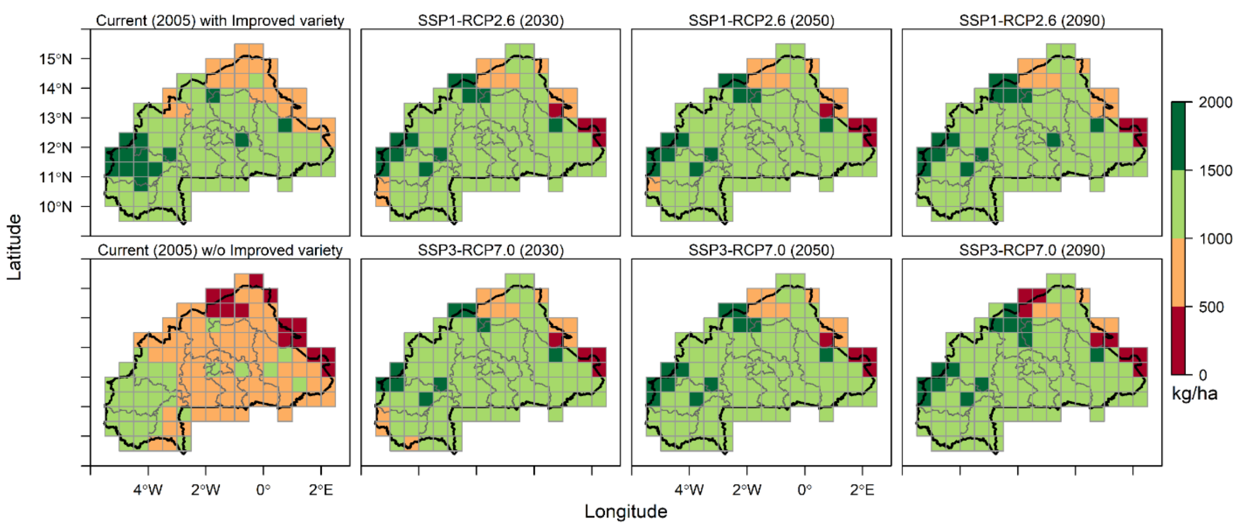

Figure 11: Spatial distribution of yields using an improved sorghum variety for various time steps and scenarios. The top row presents yields for the scenario SSP1-RCP2.6, and the bottom row presents SSP3-RCP7.0. To compare the current with future effects of adaptation, yield distribution maps of the current (2001-2016) with and without adaptation options were given in the left column.

Figure 12 shows the distribution of yield impacts when using an improved variety at the national level. The Y-axis indicates the % difference of yields between with and without improved variety adoption for various scenarios and time steps. While under SSP1-RCP2.6 yields showed similar impacts (approximately 35-45%) over time, they showed an increasing trend under SSP3-RCP7.0 in most regions. Figure A.12 shows the yield impacts of an improved variety for each region under both the scenarios and different time steps. Northern regions such as Sahel, Centre-Nord, and Nord are projected to have increased yields up to 80% when adopting the improved variety, which is similar to the spatial patterns of irrigation in all scenarios. The lowest impacts were projected in Cascadas, Haut-Bassins, Centre-Ouest, and Sud-Ouest in all scenarios.

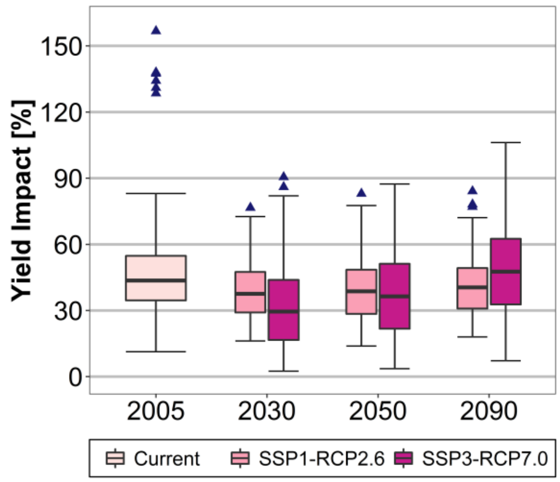

Figure 12: The boxplot presents the grid-wise yield impacts of improved variety over Burkina Faso. The X-axis indicates the time steps, and the Y-axis indicates the % difference of yields between with and without improved variety adoption (Fadda) for various scenarios and time steps (i.e., 100% indicates a doubling of the yields). The triangle points represent the outliers. The boxplots show upper, median, and lower values of the yield impacts.

3.4.4. Agroforestry

The sorghum yield benefits of agroforestry show regional divergence across Burkina Faso (Figure 13). When establishing agroforestry, yields can increase up to 150% at the grid scale and up to 120% at the regional scale in Southern Burkina Faso (Sud-Ouest, Centre-Ouest, Centre-Sud, and Centre-Est). However, yields are projected to decline over time under the high emissions scenario (SSP3-RCP7.0) in the regions mentioned above. Also, in the later time steps, the 2050s and 2090s, yields were projected to decrease in central regions such as Centre-Nord and Nord under both emissions scenarios.

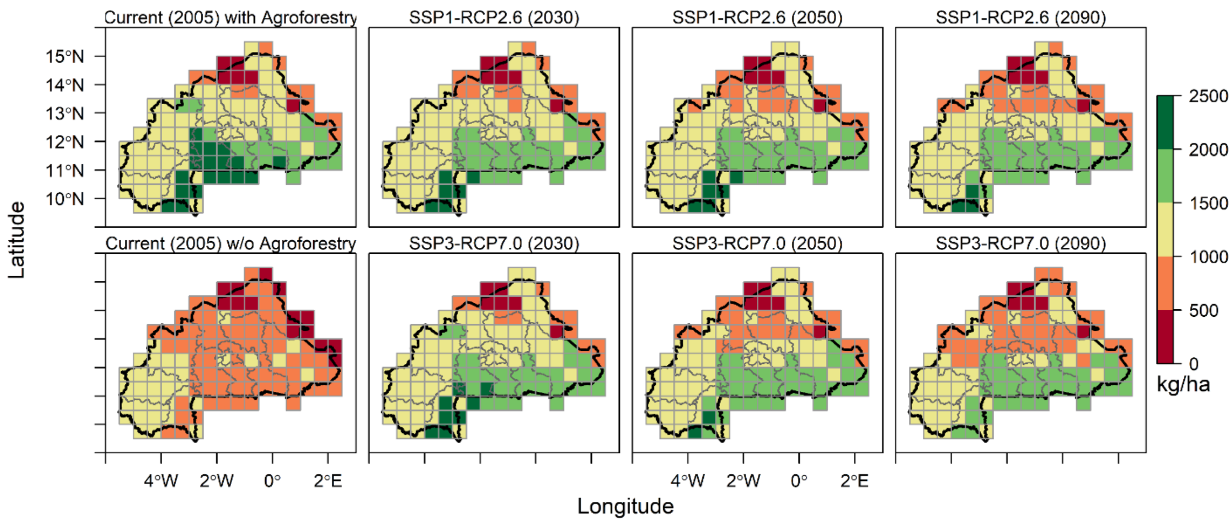

Figure 13: Spatial distribution of yield changes using agroforestry for various time steps and scenarios. The top row presents yields for the scenario SSP1-RCP2.6, and the bottom row presents SSP3-RCP7.0. To compare the current with future effects of adaptation, yield distribution maps of the current (2001-2016) with and without adaptation options were given in the left column.

Figure 14 shows the distribution of yield impacts over time under different scenarios at the national level. The Y-axis indicates the % difference in yields between with and without agroforestry systems for various scenarios and time steps. Over time, national averages under the low and high emissions scenario with the adoption of agroforestry systems show nearly unchanged impacts or a slightly decreasing trend, which is up to a 92% increase in yield than current. Figure A.13 shows the yield impacts of agroforestry for each region under both scenarios and different time steps. A few regions (Cascadas and Haut-Bassins) have a higher positive impact under the low emissions scenario (SSP1-RCP2.6) and a few (Sahel, Nord, and Centre-Nord) under the high emissions scenario (SSP3-RCP7.0). Central regions (Centre-Ouest, Centre-Sud, Centre, Plateau-Central, and Est) are projected to have nearly the same impacts under high and low emissions scenarios, except for projections until the end of the century. The regions Centre-Ouest, Centre-Sud, Centre, Plateau-Central, and Est, had higher SOC (Figure A.14) compared to other regions. Higher SOC regions are projected to have yield increases up to a 120%, and other regions have projected yield increase up to 40%.

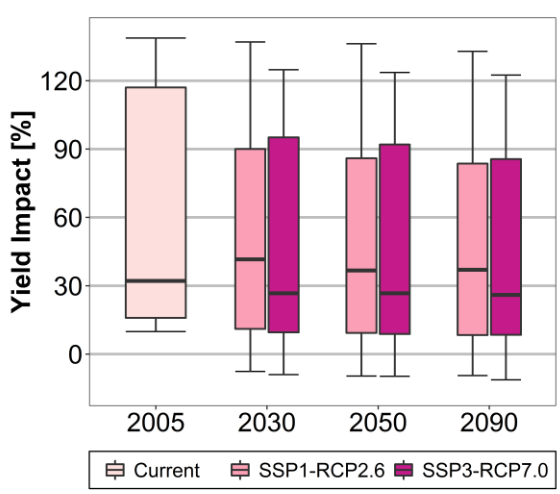

Figure 14: The boxplot presents the grid-wise yield impacts of agroforestry over Burkina Faso. The X-axis indicates the time steps, and the Y-axis indicates the % difference of yields between with and without agroforestry systems for various scenarios and time steps (i.e., 100% indicates a doubling of the yields). The triangle points represent the outliers. The boxplots show upper, median, and lower values of the yield impacts.

3.5. Comparison of adaptation strategies

A composite of the yield impacts across time, scenarios, and the four adaptation strategies are shown in Figure 15. Overall, all adaptation strategies could significantly increase yields (ISFM- up to 300%; Improved variety- up to 90%; agroforestry- up to 125%; irrigation – up to 43%) at the regional scale. However, adaptation by irrigation did not result in significant impacts on the national scale, in contrast to other adaptation measures. Across all adaptation strategies, the lowest yields were projected under SSP3-RCP7.0 for 2090, while the highest yield gains with the respective adaption option were simulated for the current period (with a slight exception for the improved variety, showing the lowest yields under SSP3-RCP7.0 for 2030). However, a few regions in the north (Sahel, Nord, and Centre-Nord) could benefit from irrigation due to water stress under both scenarios, except for the time period 2090 under the high emissions scenario. The least positive impacts were projected with irrigation on demand (the 895 kg/ha under SSP3-RCP7.0 in 2090 are close to current yields). The largest positive impacts on yields were projected with ISFM, which induces yields up to 300% (at the regional level) higher than currently attained. Agroforestry approximately doubles the current yield in a few regions, and the improved variety increases yield by about 60% compared to the current yield, showing a moderate increase in yields compared to irrigation.

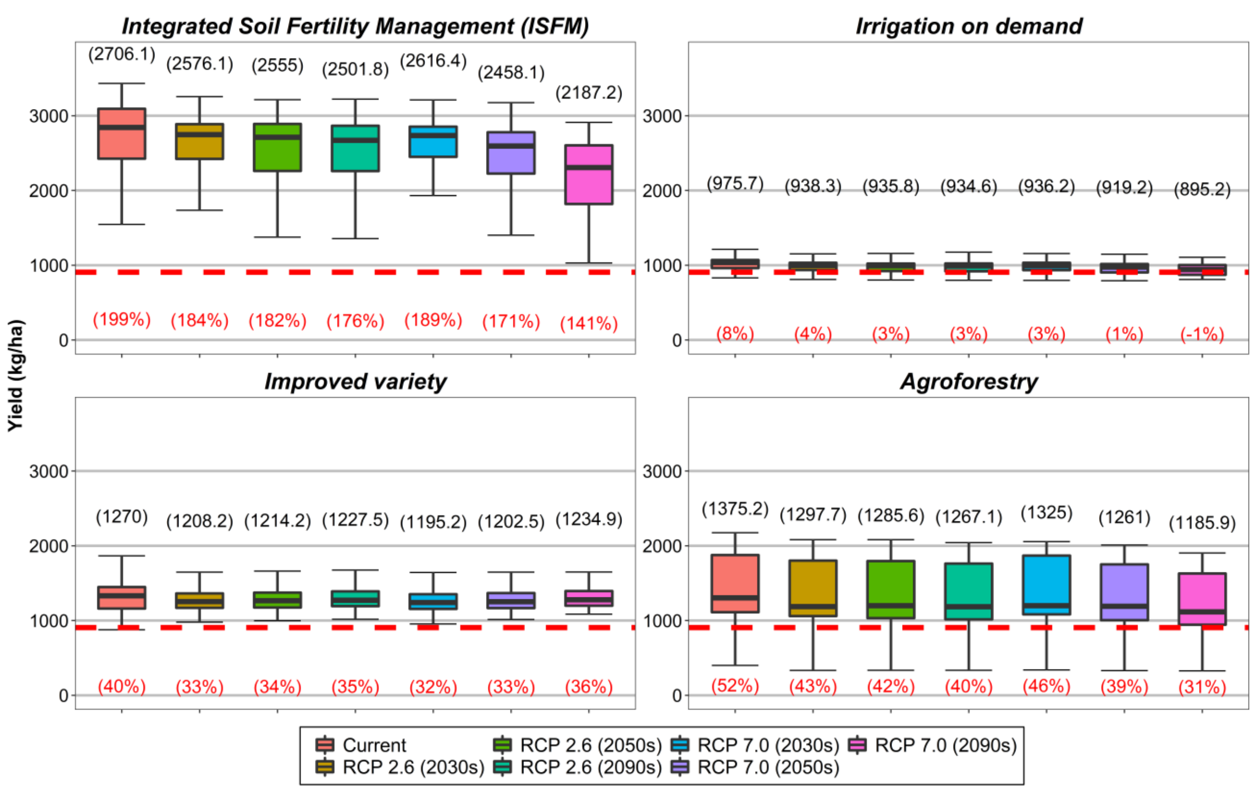

Figure 15: Comparison of all adaptation strategies over various time steps and scenarios. The boxplots show the distribution of simulated yields at the grid cell level. Lines in the boxplots represent the median, values on top of the boxplots show the mean of gridded yields (national average yield), and values on the bottom of the boxplots show the % change

in yields from the national-wise reported yield (906kg/ha). The red dotted line represents the national-wise reported yield (906 kg/ha).

4. Discussion

4.1. Historical climatic trends in Burkina Faso

The past climate data used in this study shows an increasing trend in precipitation in Burkina Faso from the 1970s on. Various other authors have also observed this rainfall recovery trend (Gbohoui et al., 2021; Lodoun et al., 2013; Nouaceur and Murarescu, 2020; Tazen et al., 2019). These increases in precipitation have contributed to the general increase in net primary production in the region (Dardel et al., 2014). However, they have also been accompanied by increases in the number of heavy precipitation events, resulting in floods and erosion (Panthou et al., 2014). Therefore, the increased rainfalls have not always translated to increased agricultural performance. Historical temperature trends in Burkina Faso are displaying a warming trend. Observations have shown increases in maximum and minimum temperatures and extreme temperature indices, as shown by our results and other studies (De Longueville et al., 2016; Kima et al., 2015). Temperature increases may partly explain why increases in precipitation have not always directly translated to increases in agricultural production in the country as it increases evaporative water losses and increases crop water requirements – apart from non-climatic factors that also impinge on agricultural productivity.

4.2. Projected climatic changes in Burkina Faso

Annual precipitation sums are projected to change in the whole country, with the magnitude and direction of change depending on the emissions scenario and the climate model. The majority of models indicate an increase in future precipitation, with possibly substantial increases under the high emissions scenario. This projected wetting trend has also been reported in the literature but varies substantially between models, especially under higher emissions (Sylla et al., 2016). In addition, and most importantly, a few models project increases in heavy precipitation intensity and frequency in the future compared to the current and historical scenarios.

Regarding the start of the rainy season, results are not conclusive as this depends on the model, the period, and the emissions scenario. The climate models project a robust warming trend in Burkina Faso over the 21st century, at worst by 3.6°C by 2090 compared to 2004 under the high emissions scenario. This warming trend is also evident as increases in temperature indices such as very hot days and tropical nights. The latter is projected to rise for nearly three quarters (75%) of the country and over 84% of the year, respectively. These indices have already been changing in the past and are projected to become worse, as also confirmed by other studies (Borona et al., 2016; Kima et al., 2015).

4.3. Current and projected sorghum yield in Burkina Faso

Model performance evaluation showed that our crop model simulated the observed annual variation of sorghum yields at the national level well in Burkina Faso. It partly overestimated sorghum yields (by 46.2 kg/ha or 4.6%, on average), which is common in many process-based crop models as these are usually calibrated with controlled environments and do not account for non-climatic factors like pests and weed pressures (Bondeau et al., 2007). Our model captured the weather-mediated changes in sorghum yields regardless of this slight overestimation. Particularly, both high and low-yielding years were adequately modeled, which is crucial for food security and climate change impact assessments. Similar crop model results have been reported for sorghum in Burkina Faso, applying WOFOST (Wolf et al., 2015) and SARRA-H (Sultan et al., 2013). In addition to the suitable model fit on the national level, the spatial distribution of sorghum yields matches between observations and simulations, with maximum yields in the western and southern areas and a decreasing gradient towards the north, as also shown in other studies (IFPRI, 2019). Given this performance in the historical period, we have confidence in applying the model for climate change impact and adaptation assessments.

We project yield losses for sorghum in Burkina Faso under climate change until the end of the century. The magnitude of the loss depends on the emissions scenario, the period, and the region. Our projected yield loss of 5.5% by 2090 is conservative at the national level compared to other projections with 8% (Adam et al., 2020) or 15% (Sultan et al., 2013) losses. While the yield changes at the national level are small, we see that the modeled sorghum yields diverge between regions: from down to 30% lower than current levels in the southern and western regions (Cascades, Haut-Bassins, and Sud-Ouest) up to yield increases in the north (Sahel, Nord, and Centre Nord). The regional distribution of climate change impacts presents an opportunity for targeted adaptation planning as efforts can be directed towards the projected yield loss regions. The current higher-yielding areas (West and South) are projected to have yield losses in the future, while lower-yielding areas (North) are projected to have gained. This could mean that a shift in areas used for agriculture could be possible.

4.4. Current constraints to implementing adaptation measures

While the model results show possible large increases in yields after applying the adaptation strategies, different constraints hinder an easy uptake. This also holds for current times, where the chosen measures would already be beneficial for yields without climate change. In terms of ISFM, significant obstacles to adopting ISFM have been highlighted. High workforce requirements and expenses are especially constraining for smallholder farmers and low-income households. Additionally, women's farms have less access to the necessary tools, which leads to lower yields on women's plots and make the women more susceptible to climate change (Kaptymer et al., 2019). Considering irrigation, according to Lèye et al., 2021, 78.4% of households believe that supplemental irrigation is a promising strategy for reducing the negative impacts of dry spells on agricultural production. However, less than 2% of cultivated areas use irrigation, leaving a majority of farmers susceptible to dry spells that can negatively impact agricultural production (FAO, 2005) due to the low purchasing power of irrigation infrastructure (Alvar-Beltrán et al., 2020) among the majority of farmers, illegal irrigation connections (Kambou et al., 2019), and limited water storage capacities.

According to Ndjeunga et al., 2015, only 3% of the area was planted with improved sorghum varieties. Several issues have hindered the adoption of improved varieties. 1) Initially, improved varieties were not suitable for the specific qualitative attributes required by value chain stakeholders such as farmers, stockbreeders, local processors, consumers, and others who influence the technical choice as they were primarily intended to optimize the agronomic criteria of yield (vom Brocke et al., 2020), and 2) Weak research-development continuum running through the agricultural extension services (Almekinders et al., 2007; Hoffmann et al., 2007; Smale et al., 2018). In terms of agroforestry implications, the technical difficulties in managing seeds and the lack of funding to cover production expenses are some of the issues that restrict the supply of seedlings (Yameogo et al., 2018), which are the main constraints.

Compared to the global average (ranging from 264 kg/ha to 18334 kg/ha at the country level with an average of 2366 kg/ha), the national yield in Burkina Faso is low (979.6 kg/ha), hinting at a large and persistent yield gap based on FAOSTAT, 2022 observations from 2000 to 2020. Possible adaptation measures should bypass the abovementioned constraints (e.g., lack of inputs such as fertilizers, irrigation infrastructure, market accessibility, agro-advisories, accessibility of improved varieties, etc.) for increasing the yield and reducing the yield gap even under the current climate conditions.

4.5. Representation of adaptation strategies in DSSAT

Using DSSAT, we quantified the impacts of climate change on sorghum yield in Burkina Faso and evaluated the potential of the following four strategies: Integrated soil fertility management (ISFM), irrigation on demand, an improved variety, and agroforestry to stabilize and enhance yields under various climate change scenarios. These adaptation strategies are outlined in Burkina Faso's National Adaptation Plan (NAP) and Nationally Determined Contributions (NDC). Our evaluation of adaptation measures provides quantitative information on the potential of adaptation measures to sustain yield under changing climate conditions, which is important for developing adaptation investment plans in the Nationally Determined Contributions (NDCs) and National Adaptation Plans (NAPs). In addition, with a gridded modeling approach, our study provides spatial information on where the selected adaptation measures are effective to enable targeted planning, prioritization, and implementation of strategies for building resilience in the agriculture sector in Burkina Faso.

4.5.1. Integrated Soil Fertility Management (ISFM)

Results of other studies showed that implementing ISFM over various regions in West Africa leads to significant yield increases, which are similar to our modeling results. For instance, in Niger's Illela district, average sorghum yields with ISFM (Zai pits) were 310% higher compared to untreated fields (Kaboré and Reij, 2004), and in various parts of Niger, ISFM produced 2 to 69 times more grain (sorghum) yields than without ISFM (Fatondji et al., 2006). Our results shows that the ISFM (Zaï) practice can triple sorghum yields in all regions of Burkina Faso, especially in low-rainfall and low-yielding regions of Burkina Faso (Sahel, Nord, and Centre-Nord). These findings underline the yield gap in the country and that climate change will impact already low-yielding regions, as reported previously (Diarisso et al., 2016; Ouedraogo et al., 2020). Therefore, with our modeling approach, we demonstrate the potential to increase sorghum yield even under a changing climate in Burkina Faso with low-cost integrated soil fertility management practices. Enhanced availability of sorghum production from ISFM may also bolster food security, economic security, the groundwater table, tree regeneration, and biodiversity (Nyamekye et al., 2018). We recommend further studies to analyze the impacts of combined Zaï and other productivity-enhancing technologies, such as improved varieties and agroforestry. Despite the advantages of this technology, it is currently not well adopted for various economic and biophysical reasons, such as lack of labor and availability of the necessary materials (Adimassu and Mekonnen, 2012).

4.5.2. Irrigation on demand

Global cereal production might increase by 35% if irrigation was applied on all rainfed cropland, with the greatest potential in Africa and Asia (Barsukova, 2018; Li et al., 2011). In addition, irrigation in Burkina Faso enhanced sorghum yields by 10% to 85% (Some, 1989). Moreover, a few studies have shown the potential of irrigation to minimize risks and increase crop yields in sub-Saharan Africa (Fox et al., 2005; Some and Ouattara, 2005). We find that irrigation can increase current yield levels up to 43% in Burkina Faso compared to current levels, especially in the water-limited northern regions, and is a suitable measure under climate change. In the country's southern parts and under both high and low emissions scenarios, irrigation does not provide significant yield benefits, possibly because of excessive evaporation losses under elevated temperatures, interception losses, deep percolation, and surface runoff due to a combination of higher rainfall and irrigation (Rockstrom, 2000). The Crop Water Requirement (CWR) of the crops in the northern regions (Sahel, Nord, and Centre-Nord) of Burkina Faso is higher than in the southern regions due to less rainfall. A combination of an increase in rainfall and irrigation in the future may help to reach potential CWR, leading to higher yields in the northern regions. Thus, irrigation is not a universal adaptation measure for Burkina Faso in terms of crop water requirement of the crops with increased rainfall and irrigation in the future. Nevertheless, irrigation could be a possible adaptation option in the Sahelion region, where it helps attain potential crop water requirements combined with rainfall. Our study also projected a possibility of reduction (at the national level) compared to the current yield with "irrigation" in the 2090s under a high emission scenario (SSP3-RCP7.0) but not with other adaptation measures. In this case, irrigation could be replaced or combined with other adaptation measures. In conclusion, we recommend and encourage conducting impact assessment studies combined with an analysis of water requirement indices like the Water Requirement Satisfaction Index (WRSI) (Tarnavsky et al., 2018) to identify region-wise scopes of irrigation interventions.

4.5.3. Improved variety

Grain yields depend on crop genetic potential in combination with agronomic practices such as plant density and fertilization, apart from the weather. Therefore, improved varieties should respond positively to plant density and nitrogen fertilizer to actually increase yields. A few experimental analyses from various parts of West Africa conducted with various improved varieties have shown significant effects: an increase in density, nitrogen dosage, and grain and straw yields up to 100% (Joseph et al., 2020). We find in our study that replacing current varieties with an improved variety will significantly increase yields under climate change in the northern, dry parts of the country. The varietal response displays spatial diversity across the country, with some regions responding more than others - which should be considered for adaptation planning. Improved varieties of sorghum have repeatedly been shown to be resilient to climate change (Coulibaly et al., 2018; Sanou et al., 2016; Vom Brocke et al., 2014). The spatial distribution of impacts of applying irrigation is similar to the adoption of improved variety (e.g., North Positive impacts in the north and slight/no changes in the south). Our impact assessment of improved varieties could help to explore the complex processes upstream (i.e., developing new varieties, market accessibility, and seed value chain) to bring such varieties to the fields. We recommend conducting studies on improved varieties combined with soil-water conservation techniques such as Zai and agroforestry to maximize compound impacts.

4.5.4. Agroforestry

Agroforestry is a putatively beneficial farming system, but it might as well not lead to positive impacts (higher tradeoff between tree canopy and crop productivity) (Neya et al., 2019) or have no significant impacts if not properly designed (Karlson et al., 2020). Yet, up to date, a plethora of studies have shown that trees inside agricultural fields (which are long-term and have less canopy) often have a positive impact on crop production (Kuyah et al., 2019), including parklands in West Africa (André et al., 2008; Roupsard et al., 2020). This is because trees contribute to improving soil fertility by replenishing nutrient levels through organic matter and nitrogen fixation or by reducing the loss of organic matter and nutrients through erosion control and promotion of nutrient recycling (Akinnifesi et al., 2010; Bayala et al., 2007; Rao et al., 1997; Sileshi et al., 2014). In this study, crop yield trends by agroforestry are projected as persistently positive across emissions scenarios, especially in the southeastern regions (Sud-Ouest, Centre-Ouest, Centre-Sud, and Centre-Est) of Burkina Faso. This is possibly due to the following reasons: a) the regions already have higher SOC (1.1-1.5) than other regions, and agroforestry systems improve SOC further (1.3-1.8), and it improves soil structure and water-holding properties, improving crop yield (Oldfield et al., 2019). b) Additionally, an increase in SOC could improve microbial activity, indicated by a rise in various enzymatic activities within a range of 1.52-1.82 SOC, which could reflect more benefits in productivity (Pawar et al., 2017). Experiments show encouraging results regarding the positive impact of SOC on crop yields and agronomic productivity (Lal, 2006). Except for southeastern regions, yields are projected to increase by 40% above current levels even under climate change. Agroforestry systems enhance productivity in multiple ways (Verchot et al., 2007). In our study, we only used SOC as a key factor in this study, as agroforestry is not natively implemented in DSSAT. Agroforestry systems may have positive side effects beyond yield augmentation, including enhanced carbon sequestration or harvesting products from trees. Along with efforts to promote farmer-managed natural regeneration (Lohbeck et al., 2020; Reij and Garrity, 2016; Zoungrana, 2020), our results increase motivation and scientific justification for such efforts.

4.6. Potential limitations

While the results are plausible based on comparison with reference data, it is imperative to point out some potential limitations and sources of uncertainties. The strength of any modeling study is in the quality of the input dataset used to parameterize/calibrate/evaluate the model (Grassini et al., 2015). The ability to model sorghum in a gridded model depends on the representation of local conditions for each grid. Nevertheless, finding quality input datasets for each grid is difficult for countries like Burkina Faso, where the data is limited and, in some cases, inaccurate. Some of the adaptation measures assessed in this study, such as ISFM and agroforestry, are not native to the DSSAT but are based on our understanding and the literature. At the same time, irrigation and improved varieties are available in the model. This representation may not be complete, and further field studies are required to build confidence in the modeling. However, the range of effects from our model results matches that reported in the literature.

Further sources of uncertainty of model results can come from projected climate data. To minimize this, we used an ensemble of ten downscaled and bias-adjusted climate models, but these models have not been evaluated for their appropriateness to use in Burkina Faso or West Africa. Overall, we believe that our results are robust and can be used in national adaptation planning and impact assessments, but users should be aware of these potential limitations.

5. Conclusions

This study simulated sorghum yields in Burkina Faso under current and projected climatic conditions and evaluated four adaptation strategies. We proposed a calibration strategy for a dynamic spatial crop model with satisfactory accuracy for allowing us to estimate the impacts of climate change and various adaptation options. Our analysis showed that adaptation measures could buffer projected yield losses in Burkina Faso. While all tested adaptation measures increased productivity substantially over current levels, ISFM (or Zaï) significantly outperforms other management options. Our suggestions were not evaluated concerning their economic feasibility, cultural acceptance, integrated multiple adaptation measures, and weighting of the adaptation strategies on a sub-national level. Nonetheless, these assessments could provide further impetus for research in local trials and the implementation by governments, non-governmental agencies, farmer's organizations, extension workers, and farmers. This study could also contribute to solving issues such as the lack of convincing demonstration that the technologies provide significant benefits.

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8. Contributor Roles Taxonomy (CrediT) author statement

Ponraj Arumugam: Conceptualization, Methodology, Modeling, Visualization, Writing- Original draft preparation. **Abel Chemura**: Conceptualization, Supervision, Reviewing and editing. **Paula Aschenbrenner**: Writing- Original draft preparation, Reviewing and editing. **Bernhard Schauberger**: Conceptualization, Supervision, Reviewing and editing. **Christoph Gornott:** Conceptualization, Supervision, Reviewing and editing.

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10. Appendices

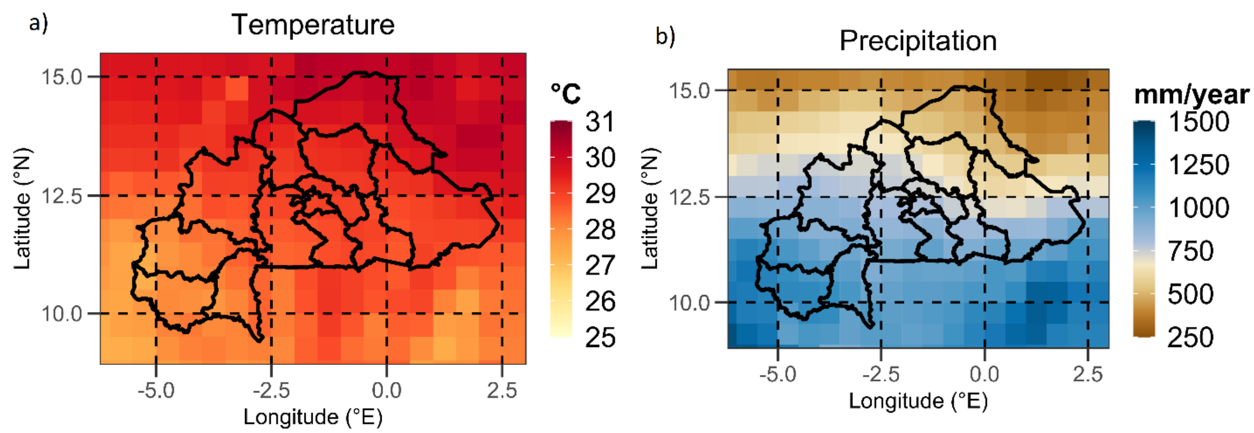

Figure A.1: Mean annual temperature and mean annual precipitation in 1997-2016 based on W5E5.

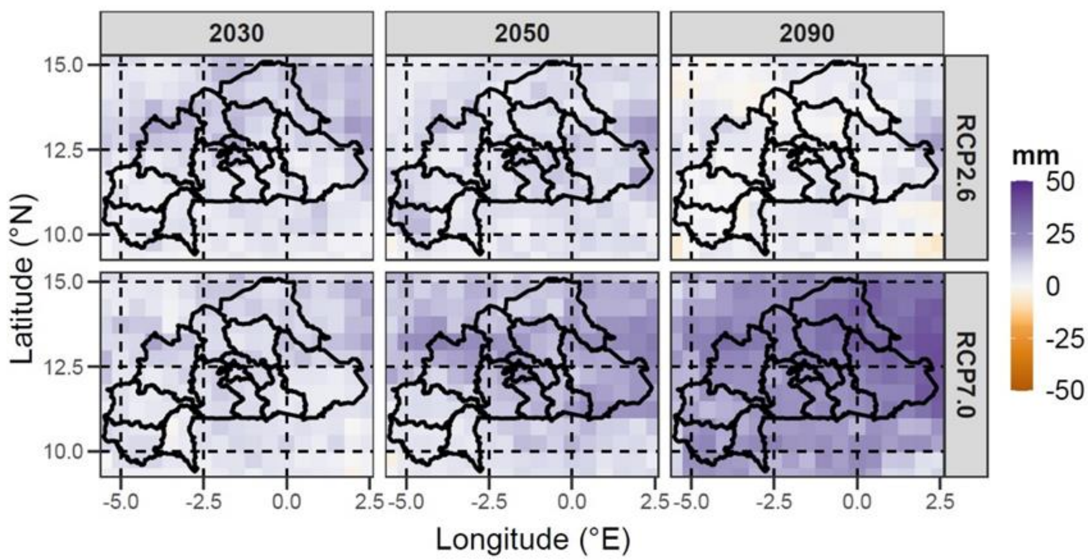

Figure A.2: Projected change in annual maximum daily precipitation in 2030, 2050, and 2090 compared to 2004 (1995-2014) under SSP1-RCP2.6 (upper row) and SSP3-RCP7.0 (lower row).

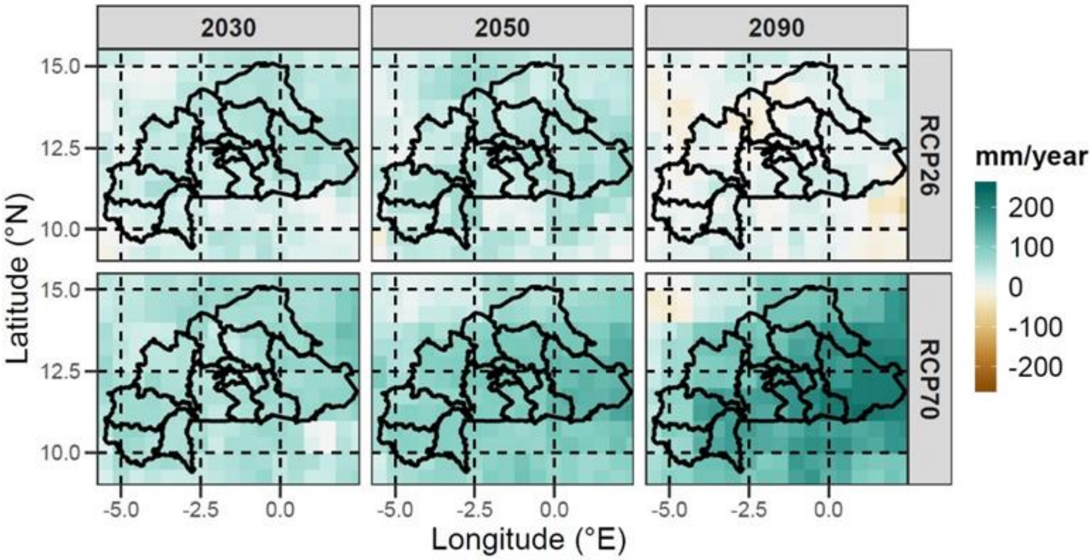

Figure A.3: Projected change in mean annual precipitation sum in mm/year in 2030, 2050, and 2090 compared to 2004 (1995-2014) under SSP1-RCP2.6 and SSP3-RCP7.0.

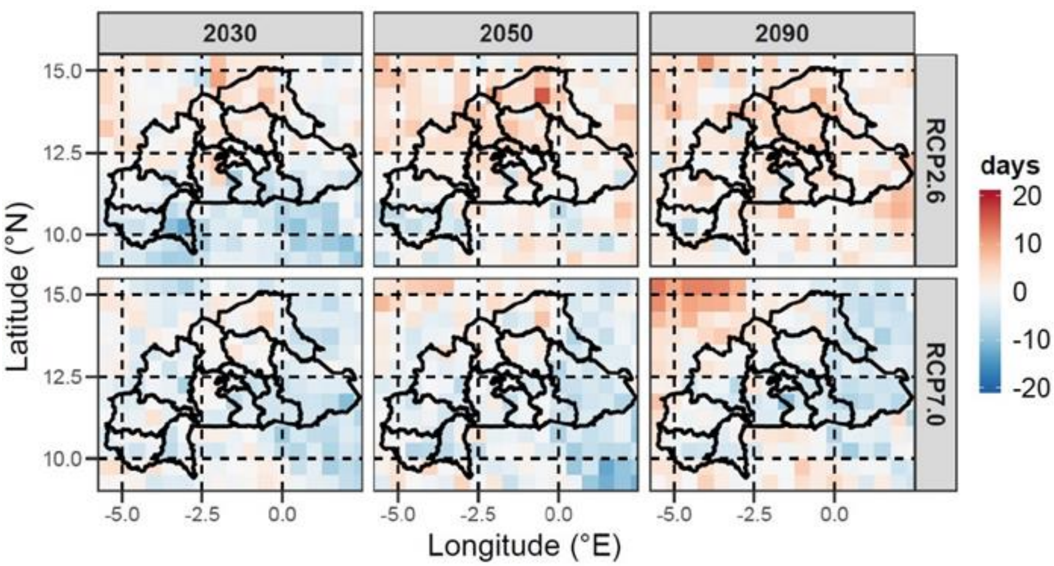

Figure A.4: Projected change in rainy season onset in days in 2030, 2050, and 2090 compared to 2004 (1995-2014) under SSP1-RCP2.6 (upper row) and SSP3-RCP7.0 (lower row). The red color indicates later rain, while the blue color indicates earlier rain.

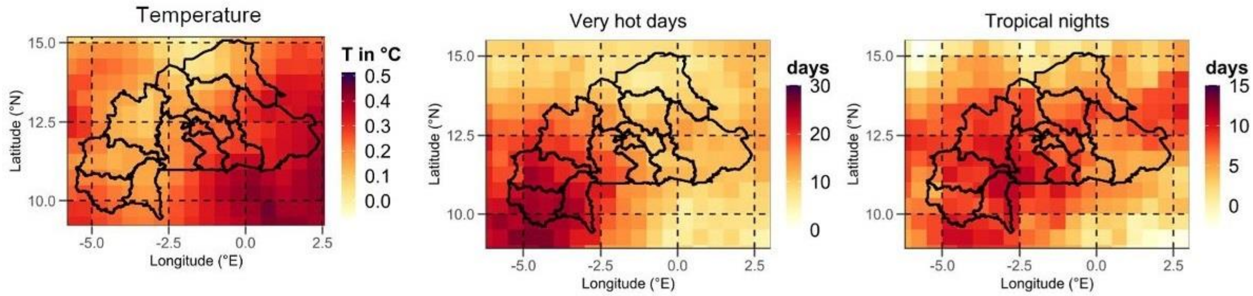

Figure A.5: Changes in mean annual temperature, number of tropical nights per year, and number of very hot days per year between 1988 – 2006.

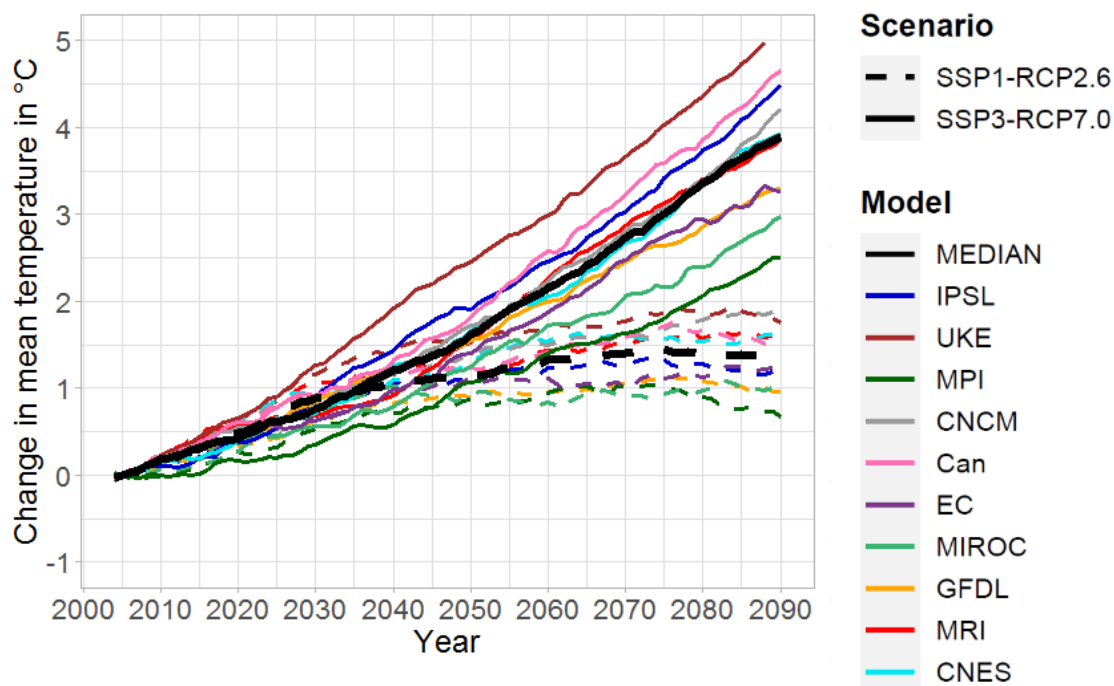

Figure A.6: 11-year moving average of the change in mean annual temperature in °C compared to 2004. Values are averages over Burkina Faso. Each variegated line indicates a projection of one of the 10 individual models. The black line displays the MMEM.

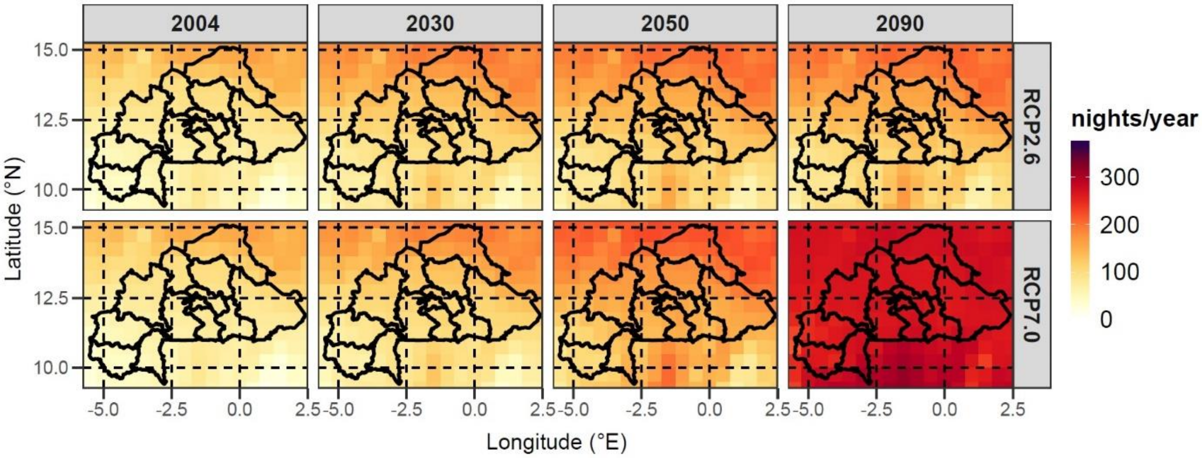

Figure A.7: Simulated and projected number of tropical nights per year for the 20-year period averages (2004, 2030, 2050, 2090) under SSP1-RCP2.6 and SSP3-RCP7.0.

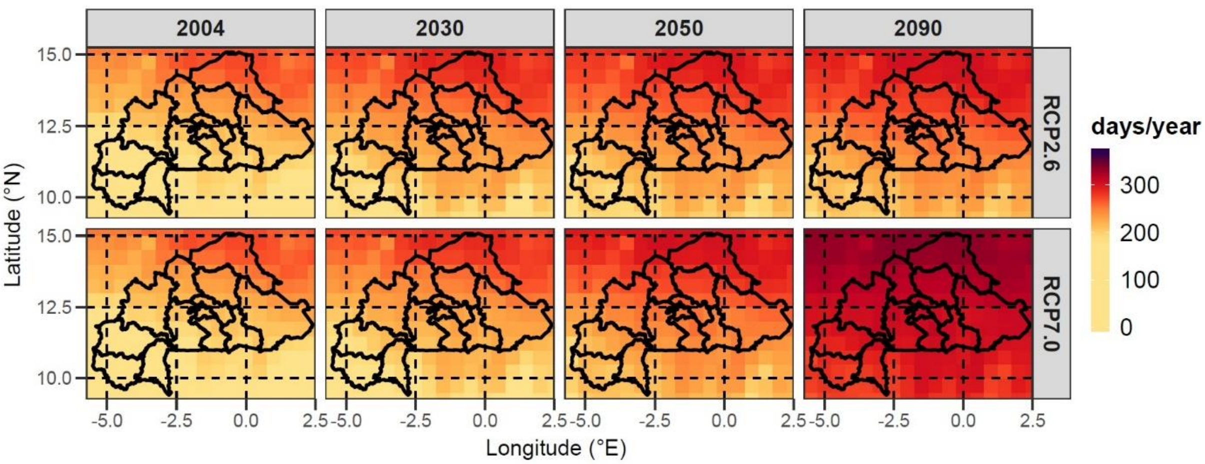

Figure A.8: Simulated and projected number of very hot days per year for the 20-year period averages (2004, 2030, 2050, 2090) under SSP1-RCP2.6 and SSP3-RCP7.0.

Table A.1: Genetic coefficients of default variety and calibrated variety

Variety	***P1***	***P2***	***P2O***	***P2R***	***PANTH***	***P3***	***P4***	***P5***	***PHINT***	***G1***	***G2***
Default	413	102	13.6	40	617.5	152.5	81.5	640	49	3	6.5
Cali-brated	463.9	102	13.6	44.94	617.5	152.5	81.5	698.8	49	3	7.154

P1 = *Thermal time from seedling emergence to the end of the juvenile phase (expressed in degree days above TBASE during which the plant is not responsive to changes in photoperiod).*
P2 = *Thermal time from the end of the juvenile stage to tassel initiation under short days (degree days above TBASE).*
P2O = *Critical photoperiod or the longest day length (in hours) at which development occurs at a maximum rate. At values higher than P2O, the rate of development is reduced.*
P2R = *Extent to which phasic development leading to panicle initiation (expressed in degree days) is delayed for each hour increase in photoperiod above P2O.*
PANTH = *Thermal time from the end of tassel initiation to anthesis (degree days above TBASE).*
P3 = *Thermal time from to end of flag leaf expansion to anthesis (degree days above TBASE).*
P4 = *Thermal time from anthesis to beginning grain filling (degree days above TBASE).*

***P5* =** *Thermal time from the beginning of grain filling to physiological maturity (degree days above TBASE).*
***PHINT* =** *Phylochron interval; the interval in thermal time between successive leaf tip appearances (degree days).*
***G1* =** *Scaler for relative leaf size.*
***G2* =** *Scaler for partitioning of assimilates to the panicle (head)*

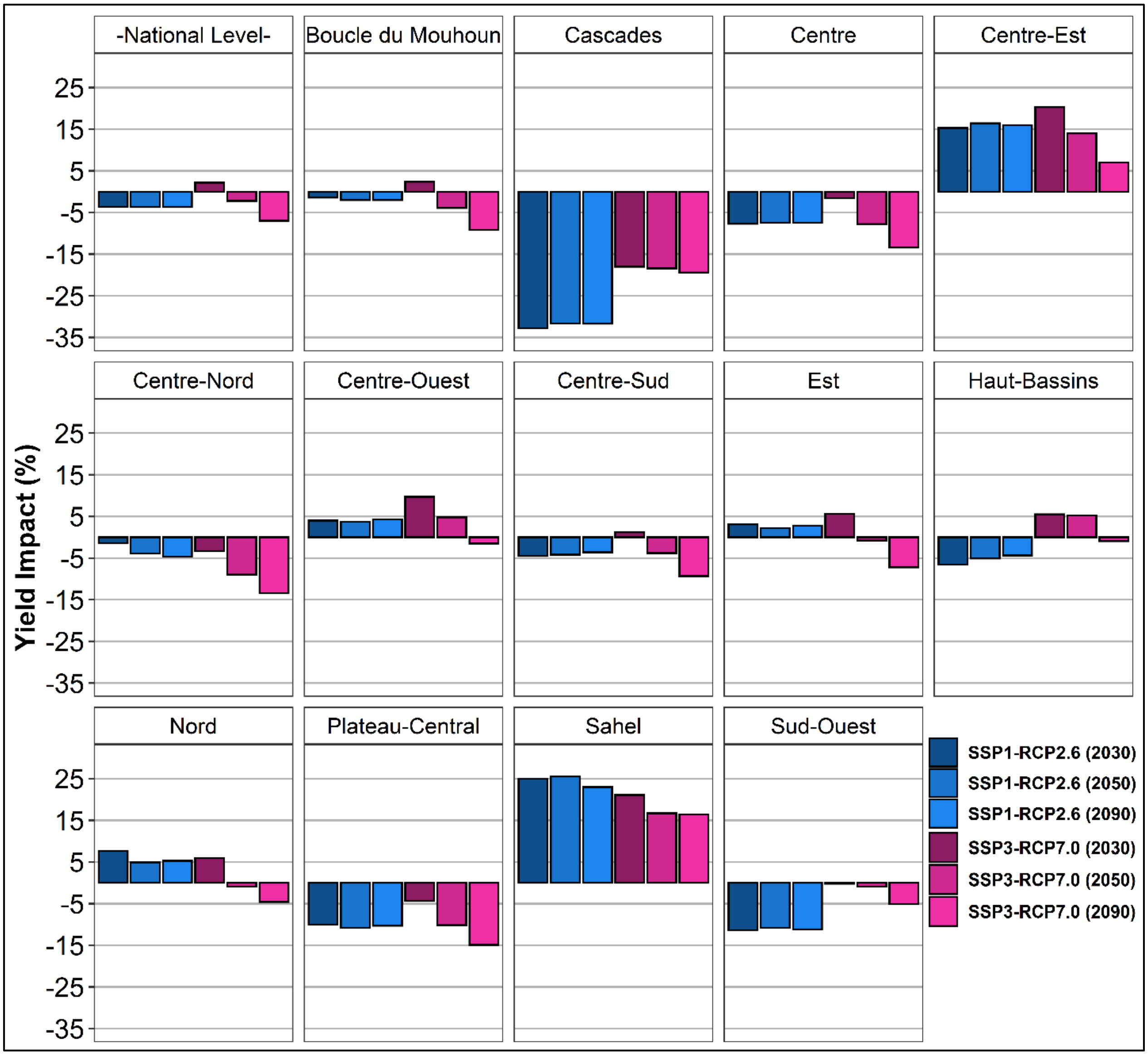

Figure A.9: Simulated yield change compared with current by region in Burkina Faso for 2030s, 2050s, and 2090s under SSP1-RCP2.6 and SSP3-RCP7.0

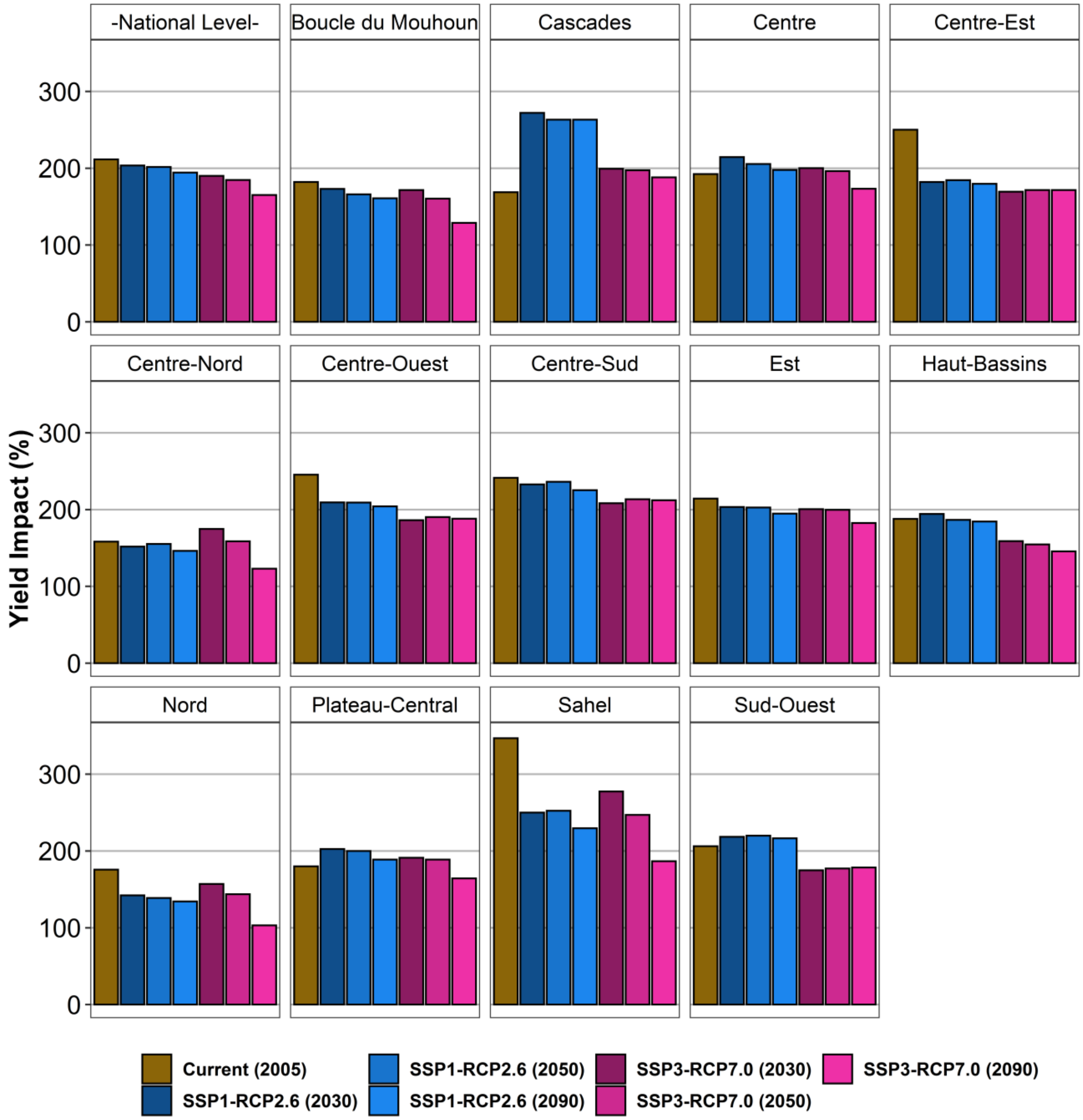

Figure A.10: Regional-wise yield impacts of ISFM for various time-steps and scenarios.

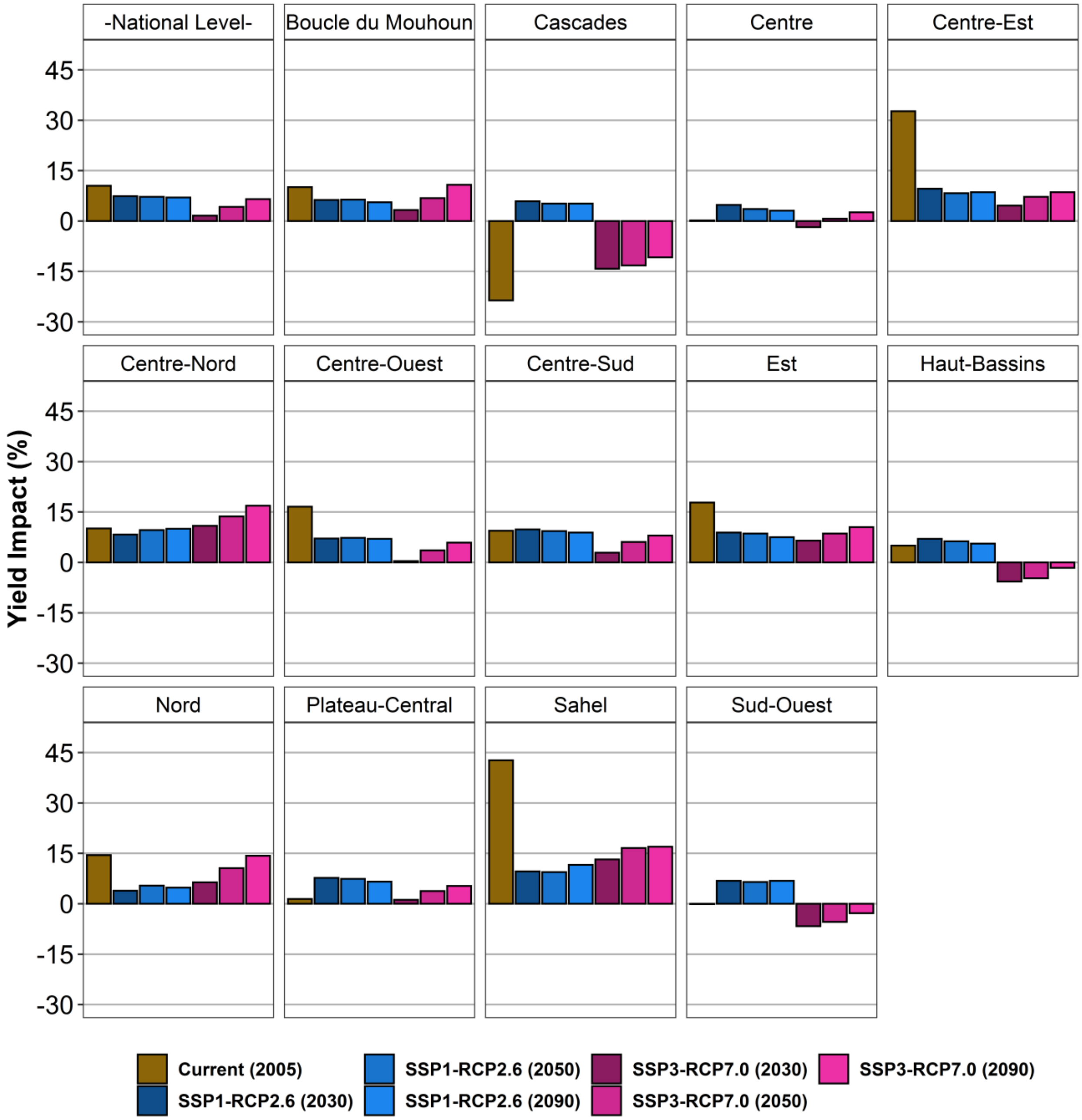

Figure A.11: Regional-wise yield impacts of automatic irrigation for various time-steps and scenarios.

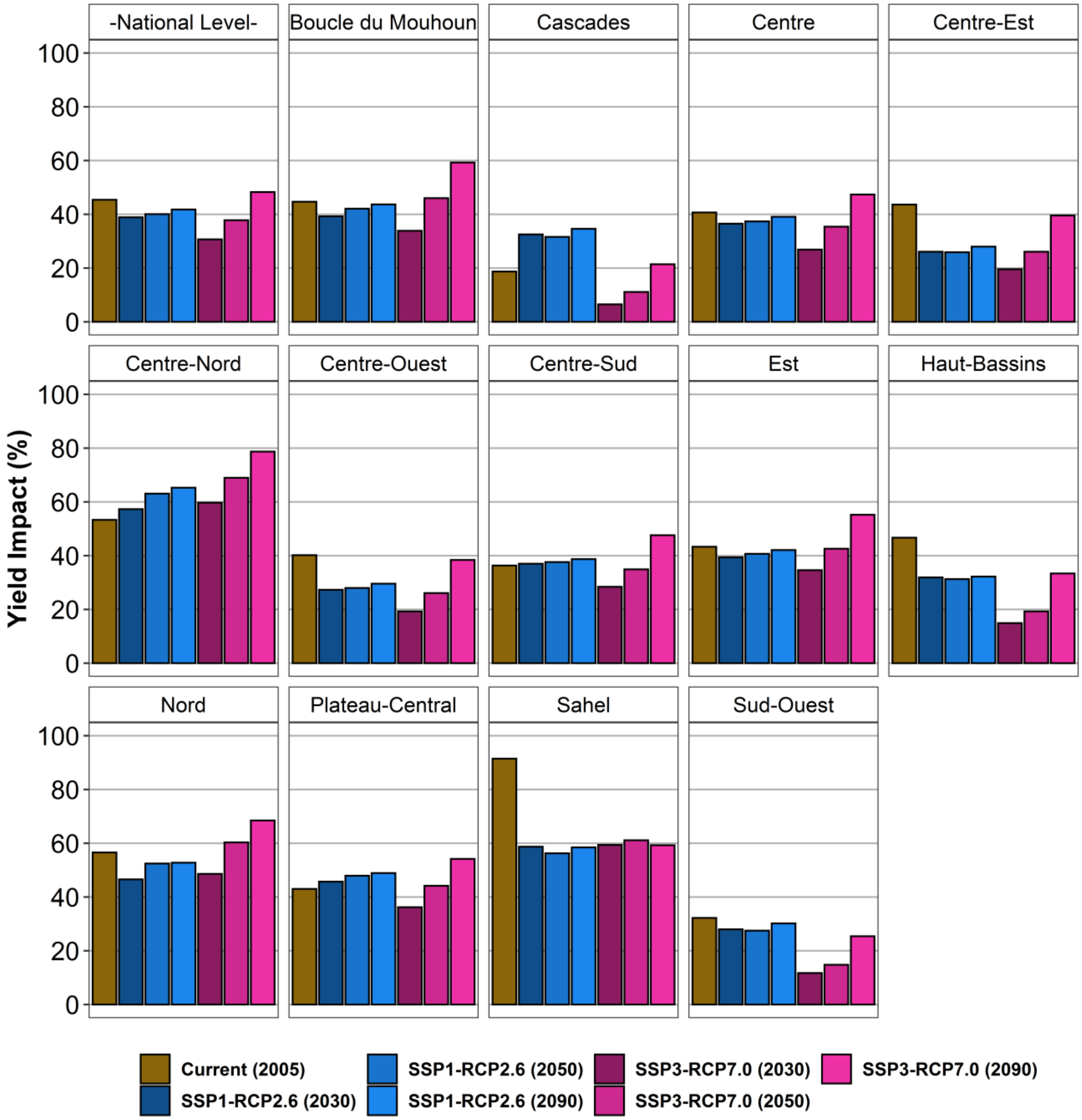

Figure A.12: Regional-wise yield impacts of improved varieties for various time-steps and scenarios.

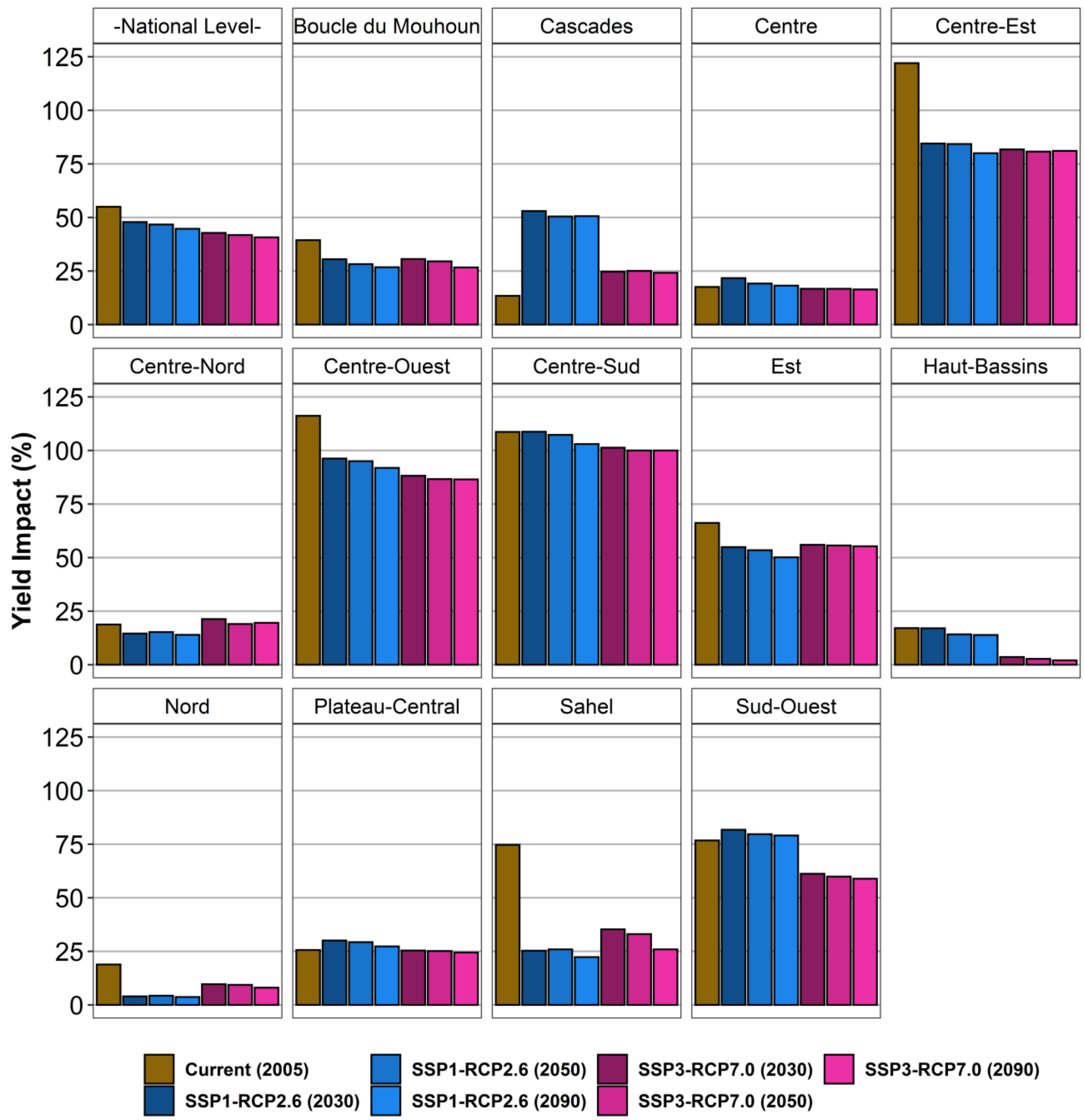

Figure A.13: Regional-wise yield impacts of agroforestry systems for various time-steps and scenarios.

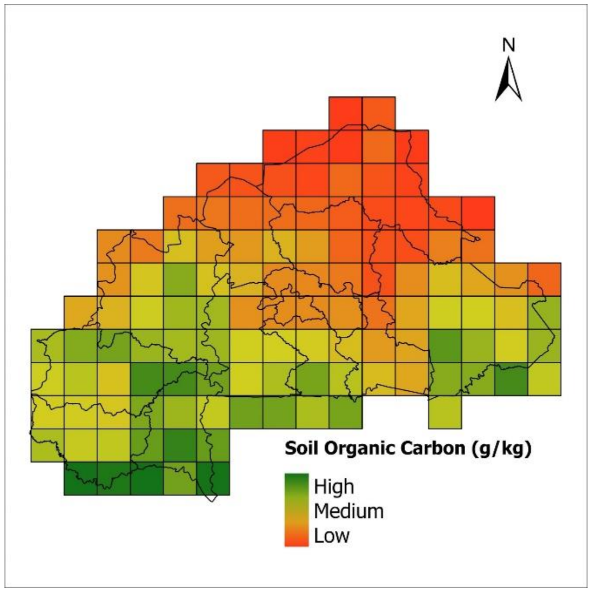

Figure A.14: Soil organic carbon of the top layer (0-5 cm) for the simulation grids