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Climate change impacts on rainfed maize yields in Zambia under conventional and optimized crop management

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Abstract

Maize production in Zambia is characterized by significant yield gaps attributed to nutrient management and climate change threatens to widen these gaps unless agronomic management is optimized. Insights in the impacts of climate change on maize yields and the potential to mitigate negative impacts by crop management are currently lacking for Zambia. Using five Global Circulation models and the WOFOST crop model, we assessed climate change impacts on maize yields at a 0.5° × 0.5° spatial resolution for RCP 4.5 and RCP 8.5 scenarios. Impacts were assessed for the near future (2035-2066) and far future (2065-2096) in comparison with a reference period (1971-2001). The surface temperature and warm days (above 30 °C) are projected to increase strongly in the southern and western regions. Precipitation is expected to decline, except in the northern regions, whereas the number of wet days declines everywhere, shortening the growing season. The risk of crop failure in western and southern regions increases due to dry spells and heat stress, while crops in the northern regions will be threatened by flooding or waterlogging due to heavy precipitation. The simulated decline in the water-limited and water- and nutrient-limited maize yields varied from 15 to 20% in the near future and from 20 to 40% in the far future, mainly due to the expected temperature increases. Optimizing management by adjusting planting dates and maize variety selection can counteract these impacts by 6-29%. The existing gaps between water-limited and nutrient-limited maize yields are substantially larger than the expected yield decline due to climate change. Improved nutrient management is therefore crucial to boost maize production in Zambia.

Keywords Climate change · Maize · Crop yields · Management · Nutrients and Zambia

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1 Introduction

Rainfed agriculture in Sub-Saharan Africa (SSA) is characterized by threats of crop failure due to multiple stresses with the most important ones being climatic conditions and nutrient deficiencies. A balance is needed between achieving food security without degrading the environment by sustainably improving yields in places where yield gaps exist (Foley et al. 2011; Van Ittersum et al. 2016). This is particularly true for maize, being one of the most important staple crops in SSA, used for consumption, livelihoods, and food security (Schlenker and Lobell 2010). In Zambia, as in many countries in SSA, maize is commonly grown by rainfall-dependent smallholder farmers affecting both the national economy and household food security (Arslan et al. 2015; Love et al. 2006; Schlenker and Lobell 2010). In 2017, maize was harvested from 1.4 million hectares of arable land (Faostat 2020) within highly variable farming systems across Zambia (Dradri 2005).

In Zambia, substantial yield gaps exist between water-limited (Yw) and actual yields (Ya) (Chikowo 2016). Existing yield gaps are mainly due to nutrient management. However, climate variability and change threatens to exacerbate yield gaps and increase inter-annual yield variability (Kotir 2011; Ray et al. 2015) in particular due to changes in temperature and precipitation (Challinor et al. 2014; Hoffman et al. 2018; Lobell et al. 2011a; Makondo and Thomas 2020; Peichl et al. 2019; Rurinda et al. 2015; Warnatzsch and Reay 2020). Since changes in temperature and rainfall intensity will vary on both temporal and spatial scale, it is important to have spatially explicit insights into their impact on crop production (Liu et al. 2012; Rurinda et al. 2015). Understanding maize yield responses to climatic changes and impact of adaptation measures is key to a climate-resilient maize cultivation (Becsi et al. 2020; Lobell and Burke 2008).

Understanding the spatiotemporal impacts of climate change is useful, because it facilitates region-specific knowledge for policy and adaptation measures or priorities to tackle those impacts (Challinor et al. 2009). For instance, agronomic management such as planting dates, varieties selection, irrigation, and residue management has been evaluated as successful adaptation measures (Brüssow et al. 2019; Challinor et al. 2014; Karapinar and Özertan 2020). In addition, insight in the impacts of climate change on Yw is also relevant for use in fertilizer recommendations, since the water-limited yield determines crop nutrient requirement (Sherene et al. 2016). Recommended fertilizer doses guided by target yields are usually designed to fulfill this nutrient requirement given soil nutrient thresholds (Sandal et al. 2008; Singh et al. 2004) thereby minimizing adverse environmental impacts due to overfertilization (Xu et al. 2013). Accurate insight into Yw and the expected changes therein due to climate change is therefore key for governmental fertilizer subsidy programs that focus on optimum fertilizer composition and application guidelines (Chapoto et al. 2016; Xu et al. 2009). Future proof fertilization recommendations require therefore spatially explicit insights in the evolution of water-limited yields.

In addition to nutrient management, it is also important to evaluate the impact of possible adaptation measures such as altering planting dates, crop types, varieties, fertilizer application, irrigation, and other agronomic management practices, given their potential to counteract climate-induced changes in crop yield (Brüssow et al. 2019; Challinor et al. 2014). Studies have shown that temperatures and precipitation changes in the short term can be mitigated by adjusting planting dates and crop variety in China (Liu et al. 2013; Zhao et al. 2015).

Currently, insights in the mitigation potential of the agronomic crop and fertilizer management under expected climate change in Zambia are lacking, in particular for the potential of combined management measures. These insights are critical because the response of crops to interaction of climate change and agronomic management varies with location. Therefore, we assessed expected large-scale and long-term changes in maize yields due to climate change and evaluated the yield response to agronomic management using the best combination of varieties and planting dates. These insights provide support to improve management strategies that help maize farmers to cope with upcoming climatic changes. In this study, we take, however, a large scale field-level assessment as a basis for policymaking, and there is a need to contextualize model assessments for decision-making at the farm system level (Silva and Giller 2021), while accounting for the variation over the country (Nissan et al. 2019).

2 Methods

2.1 Overall approach

This study takes a modeling approach to analyze the potential impacts of climate change and adaptive management on water-limited (Yw) and water- and nitrogen-limited (Yn) maize yields in Zambia under two climate change scenarios. Impacts on yield were evaluated for two time periods (near future: 2035-2066 and far future: 2065-2096) in comparison with a reference period (1971-2001). Our study focused on the relative changes in crop yield potential of maize at the country level, using a 0.5° × 0.5° spatial resolution.

There is a large variation in Zambia with respect to management practices and soil properties that affect maize yields. Climatic conditions also vary with average annual rainfall ranging from 700 mm in the south to 1200 mm in the north and an annual average temperature ranging from ca 15 °C to 32 °C (Jain 2007). Lastly, there is regional variation in farming systems, with predominantly smallholders in the south and commercial farms in the north of Zambia, each with different access to water, fertilizers, and manure. These variations have to be accounted for when one aims for an accurate assessment of yield potentials for maize. However, since our study focuses on large-scale relative changes in Yw and Yn over the coming 30-60 years, we aggregated and averaged the variation in management, soils, and climate to a spatial resolution of 0.5 degrees, the resolution of the available climate projection data. This assumption is supported by the fact that the uncertainties arising from the projected climate data likely exceed those from local variation in soil properties and management. To reduce these uncertainties, we used five GCMs ensemble averages to quantify the changes (Dale et al. 2017). We used the model WOFOST for evaluating crop response to changing climatic conditions. Model-related uncertainty given model structure, parameters, and initial conditions is relevant, but has little impact on the predicted relative change in yield potentials, being the focus of this study. The impact of the aforementioned uncertainties is discussed in more detail later.

2.2 Study area and data aggregation

Zambia is located in southern Africa between longitudes 21°E to 34°E and latitude 8°S and 18°S. The country is approximately 725,615 km^2 and has a subtropical climate. Three major agroecological regions have been distinguished, called AER I, II, and III (Chikowo 2016; Veldkamp 1987). The climatic projection data used has a 0.5° × 0.5° spatial resolution (Hempel et al. 2013), and hence, the country was divided into those grid cells for model calculations. Both climate and maize yields were analyzed for each grid cell, and the corresponding dominant soil types were derived from soil texture maps (Hengl et al. 2015). Soil textures were subsequently aggregated into generalized default soil types used in the WOrld FOod STudies (WOFOST) crop model, being coarse (EC1), medium (EC2), and medium fine (EC3) textured soils. This soil classification is highly driven by soil hydrological properties controlling crop yield such as hydraulic conductivity, water retention, and workability. Using the USDA classification, sandy soils (with 86-100% sand) were classified as coarse-textured (EC1) soils. Loamy sands (with 70-86% sand, <30% silt, and <15% clay) were classified as medium textured (EC2) soils and sandy loam soils (50-70% sand, <50% silt, and <20% clay) were classified as medium fine (EC3) soils. For visualization, maize crop areas were selected using a spatial overlay with data of the Spatial Production Allocation Model (IFPRI 2019) at a 5 arc-minute resolution. Model results are reprojected using bilinear interpolation for numeric variables and nearest neighbor for categorial ones.

2.3 Climate projections

Bias-corrected data from five selected Global Circulation Models (GCMs) in the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP), at a 0.5°× 0.5° resolution and a daily timestep, were used to gain insights into the past and projected future climate (Hempel et al. 2013). The selected GCMs included GFDL-ESM2M (Dunne et al. 2012; Dunne et al. 2013), HadGEM2-es (Collins et al. 2011), IPSL-CM5A-LR (Dufresne et al. 2013), MIROC-ESM-CHEM (Watanabe et al. 2011), and NorESM-M (Bentsen et al. 2013). Two RCPs were explored, i.e., RCP 4.5 (moderate climate change) and RCP 8.5 (severe climate change) (van Vuuren and Carter 2014). In each RCP, the ensemble average from the GCMs was analyzed for temperature and precipitation indices using Climate Data Operators (Schulzweida 2018). The indices analyzed included average surface temperature, summer days[1], precipitation, and wet days[2]. To analyze the change in an index, the difference was calculated between the reference period and a future time period.

2.4 Maize yield modeling

2.4.1 Maize yield analysis

The impact of climate change, current conventional, and optimized management on maize yields was evaluated. To understand the impact of changes in temperature, maize potential production (Yp) was simulated assuming that water and nutrients were not limiting (de Wit et al. 2019; Van Diepen et al., 1989). In addition, to analyze the impact of changes in precipitation, we simulated water-limited rainfed maize production while assuming that nutrients are not limiting. Lastly, to gain insights into the effects of current management on maize yields, the water- and nitrogen-limited maize yields were simulated. We focused on N limitation as a proxy for nutrient management. We additionally explored the impact of optimized management (varieties and planting dates) on Yw using 77 combinations of varieties and planting dates (Table 1). The optimal combination of variety and planting date

[1] Number of days where maximum of temperature is above a specified threshold in degree Celsius. In this study, our threshold were 30 °C and 35 °C.

[2] Number of days per time period with daily precipitation of at least 1 mm.

was identified by the highest mean yield, the lowest standard deviation, and the highest lower (25^{th}) quartile.

2.4.2 WOFOST model

The WOFOST model (de Wit et al. 2020) was used to simulate maize production, being a well-known model that has been used in Zambia (Wolf et al. 1987) as well as in regional and global studies (e.g., (Chen et al. 2020; Droppers et al. 2021; Wolf et al. 2015)) including the derivation of the Global Yield Gap Atlas. Crop growth and production were simulated on a daily timestep as determined by crop type, soil type, hydrologic conditions, and weather (Van Diepen et al., 1989). Main processes in the model include phenological development, leaf development, and light interception, CO_2 assimilation, root growth, transpiration, respiration, partitioning of assimilates to various storage organs, and dry matter formation (de Wit et al. 2019; Van Diepen et al., 1989). Nutrient dynamics are implemented based on the methods described in (Shibu et al. 2010), while the influence of CO_2 on crop growth is described in (Supit et al. 2012). Processes controlling water requirements, consumption, and deficits are described in (Supit et al. 2010). Impacts of heat stress (high temperatures) are included by (i) an increased water requirement, thus increasing water stress, and (ii) a temperature-dependent reduction of assimilation rates. The optimal temperature range for maize growth is between 20 and 30 °C where the assimilation rate is at maximum. The assimilation rate slowly decreases by 5% when the temperature increases up to 36 °C, after which is further decreases down to 44% of the maximum at a temperature of 42 °C. At higher temperatures, the assimilation rate continues to decrease and stops around 52 °C. Details are given in the WOFOST manual (de Wit et al. 2020).

2.4.3 Model parameterization

WOFOST was run with daily values of radiation, minimum and maximum temperature, early morning vapor pressure, wind speed and precipitation obtained from the GCMs. Information on soil water retention and hydraulic conductivity as a function of soil moisture tension were based on default values for each soil type (Van Diepen et al., 1989). In the water- and nutrient-limited simulation, we applied 112 kg/ha of N which is the blanket N recommendation rate in Zambia (Xu et al. 2009), while ensuring that phosphorus and potassium are sufficiently available at planting. The Nitrogen Use Efficiency (NUE), defined as the total N uptake divided by the total N input, was set at 50% based on the global estimate of 47% (Lassaletta et al. 2014) since actual estimates for Zambia are lacking. Though some studies showed NUE values for SSA above 100% (Edmonds et al. 2009; Pasley et al. 2020) representing a mining situation, we focused on long-term sustainable maize production and selected a reasonable NUE value of 50% for African croplands (Bouwman et al. 2013).

We used the standard crop parameter sets of WOFOST, originally compiled by van Heemst (1988) and Boons-Prins et al. (1993), and since then regularly updated with field experimental data. In this study, we used the calibrated crop parameters for maize in SSA from Wolf et al. (2015). A standard tropical maize variety (maiz.w41) was modified by successively adjusting the Temperature sums (Tsum1 and Tsum2) in intervals of 100 degrees, resulting in multiple maize varieties (Table 1). Tsum1 controls the degree days for the period between emergence and anthesis while Tsum2 determines the degree days between anthesis and maturity. Variation in Tsum was derived from experimental data of maize varieties in Zambia where silking

Table 1 Details on varieties 1-11 (left column) and planting date 1-7 (right column) used in the optimization simulation. Tsum 1 is calculated for the degree days in the period between emergence and anthesis, while Tsum 2 refers to the period between anthesis and maturity

Variety	Tsum1	Tsum2	Planting date	Planting date
1	685	786	1	28th October
2	732	839	2	7th November
3	779	892	3	17th November
4	825	946	4	27th November
5	872	999	5	7th December
6	918	1053	6	17th December
7	965	1106	7	27th December
8	1012	1159		
9	1058	1213		
10	1105	1266		
11	1151	1320		

occurred around 54-73 days after planting. Maize planting dates in Zambia currently fall between 20th November and 5 December (Chikowo 2016), where we explore planting dates between 28th October and 27th December (Table 1). To gain insights into the effect of management on crop yields, we compared two types of management approaches:

(a) Conventional management, characterized by a fixed planting date (26th November) and a common average-performing maize variety (Tsum= 1671) over the whole country.
(b) Optimized management, characterized by all combinations of 11 varieties and 7 planting dates over the country (where the best option is selected for each grid cell).

3 Results

3.1 Climate indicators

3.1.1 Temperature

Given climate change, the temperature is likely to increase by approximately 2 °C in both the near and far future. This increase in temperature is coupled with an increase in summer days (Table 2 and Fig. 1), and both factors substantially affected maize growth and yield. When both future climate scenarios are compared, it is evident that the magnitude of temperature changes increased over time. The magnitude of increase was stronger in the far future and in the severe climate change scenario (RCP8.5). The spatial distribution of the expected changes was similar in both RCP scenarios. The increase in summer days (days above 30 °C) was stronger in the southern and western parts of the country (Fig. 1). Compared to the reference period, the near future scenarios were projected to have up to 60 more summer days and up to 140 days in the far future. In addition, the number of summer days above 35 °C increases up to 10 days in the near future and up to 30 days in the far future. The average surface temperature increased on an east-west gradient, with an increase up to 2.6 °C in the near future and up to 4.6 °C in

Table 2 Average temperature and precipitation indices expressed as absolute values and as relative change comparing the historical average to two future periods

Index	Time period	Absolute				Relative change			
		Minimum	Mean	Maximum	Standard deviation	Minimum	Mean	Maximum	Standard deviation
	Reference period	17.2	21.9	26.7	1.4				
Average surface temperature (°C)	RCP 4.5 (near future)	18.9	23.9	29.4	1.4	0.79	1.99	3.55	0.38
	RCP 4.5 (far future)	19.7	24.5	29.4	1.4	1.5	2.64	3.88	0.41
	RCP 8.5 (near future)	18.9	24.4	29.9	1.5	1.15	2.54	4.65	0.56
	RCP 8.5 (far future)	20.9	26.5	31.8	1.5	2.82	4.6	6.59	0.64
Summer days (above 30°C)	Reference period	0	1	45	5				
	RCP 4.5 (near future)	0	11	119	17	0	10	74	13
	RCP 4.5 (far future)	0	18	145	23	0	16	101	19
	RCP 8.5 (near future)	0	17	132	21	0	16	88	17
	RCP 8.5 (far future)	1	60	218	41	1	59	198	37
Annual precipitation (mm)	Reference period	424	1037	2144	285				
	RCP 4.5 (near future)	432	1023	2044	289	-100	-15	44	23
	RCP 4.5 (far future)	414	1024	2032	303	-112	-14	80	33
	RCP 8.5 (near future)	406	1042	2127	294	-46	4	79	24
	RCP 8.5 (far future)	381	1010	1911	316	-232	-27	134	53
Wet days	Reference period	87	141	219	32				
	RCP 4.5 (near future)	82	136	218	33	-10	-5	-1	2
	RCP 4.5 (far future)	78	134	218	34	-14	-7	1	3
	RCP 8.5 (near future)	82	135	217	33	-13	-6	-1	2
	RCP 8.5 (far future)	75	130	217	36	-23	-11	1	4

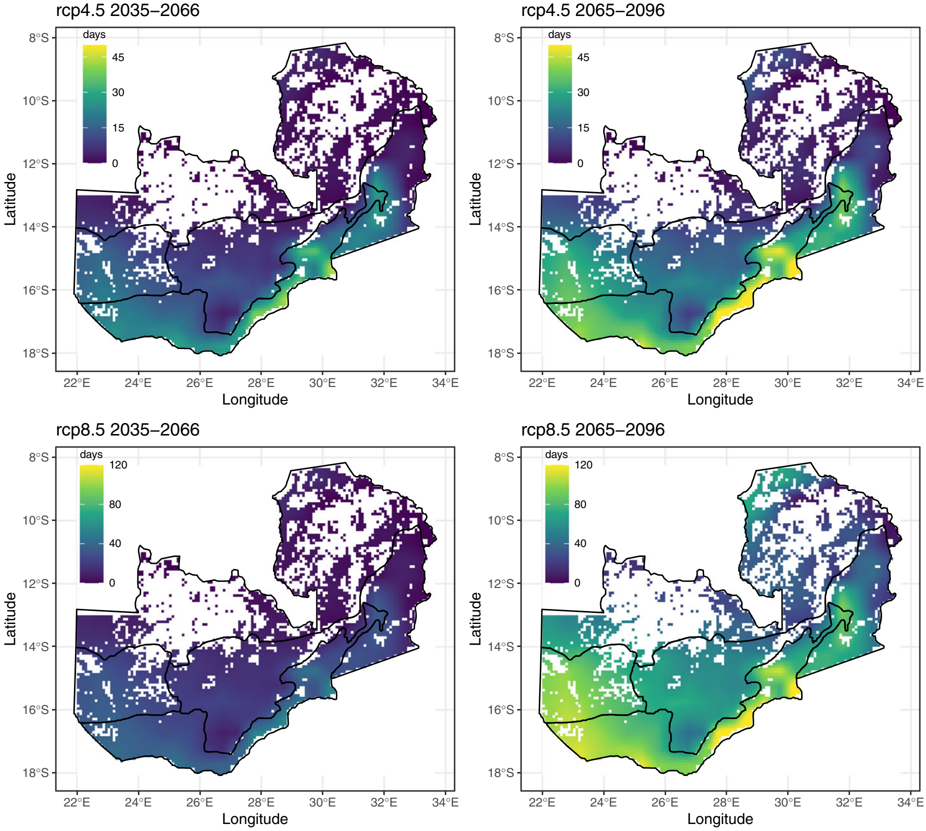


Fig. 1 Projected spatial variation in the relative change in summer days (above 30 °C) in 2035-2066 and 2065-2096 under climate scenarios RCP 4.5 and RCP 8.5 as compared to the reference period (1971-2001)

the far future. During the maize growing season, the projected temperature increased in the October-December period for RCP 4.5 and 8.5 is 2 °C and 3 °C (near future) and 3 °C and 5 °C (far future). Further projections for the period January-March, the temperature increased by 1.6 °C and 2.2 °C (near future) and 2.2 °C and 4 °C (far future) for RCP 4.5 and RCP 8.5 respectively

3.1.2 Precipitation

Over the whole country, the number of wet days was likely to decline (Table 2). In the near future, the number will reduce by 5 and 6 days, while in the far, future it decreases by 7 and 11 days for RCP 4.5 and RCP 8.5 respectively. The reduction in wet days was stronger towards the south-west regions. On average, both RCP scenarios showed a general reduction in the annual precipitation, but it increased in the northern and decreased in the southern-western regions (Fig. 2 and Table 2). In future projections, there was a reduction of precipitation in the onset of rain season and increase towards end of the season (Data not shown here).

3.2 Maize yields

3.2.1 Spatial variation in potential, water-limited, and water- and nutrient-limited yields in the reference period

In the reference period, the potential yields (Yp) ranged from 5.3 to 15.3 tons/ha with a mean of 9.9±1.4 tons/ha, whereas the water-limited yields (Yw) ranged from 4.0 to 15.0 tons/ha with a mean of 9.5±1.6 tons/ha (Fig. 3). The averaged Yw was slightly lower than predictions given in Global Yield Gap Atlas (GYGA), which is on average 11.3 tons/ha. The water- and nutrient-limited yield (Yn) ranged from 2.4 to 5.6 tons/ha with an average yield of 4.7±0.7 tons/ha. The difference between Yw and Yn was 4.8 tons/ha. Currently, the lowest yields were found in the western and southern parts of the country, being part of agroecological region I (Fig. 3). The Yn was almost 2 ton/ha higher than the average actual yield (Ya), which varied between 2 and 3 ton/ha (www.yieldgap.org accessed on: 23/03/ 2020).

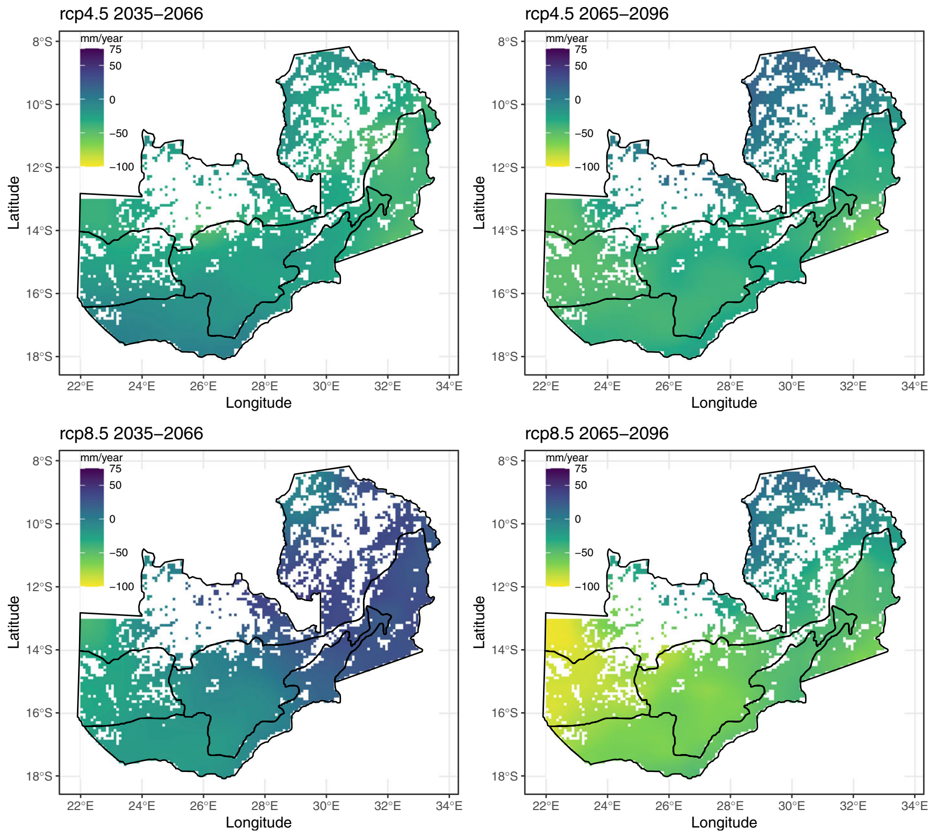


Fig. 2 Projected spatial variation in the relative change in average annual precipitation (mm·yr-1) in 2035-2066 and 2065-2096 under climate scenarios RCP 4.5 and RCP 8.5 as compared to the reference period (1971-2001)

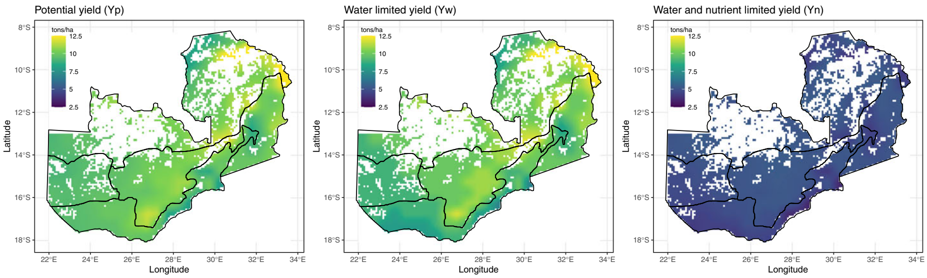


Fig. 3 Simulated spatial variation in potential yields (Yp), water-limited yields (Yw), and water- and nutrient-limited yield (Yn) during the reference period (1971-2001)

3.2.2 Relative changes in maize yields due to temperature and precipitation changes

Table 3 shows that in the near future, the Yp declined due to increased temperature in both RCP 4.5 and 8.5. Yield declined with 1.4 to 2.0 tons/ha, being equal to a decline of 15% to 21% compared to the Yp in the reference period. In the far future, a country average reduction of 1.9 ton/ha (20%) for RCP 4.5 and 3.5 tons/ha (36%) for RCP 8.5 is expected. For both RCPs, the decline in Yw equaled the decline in Yp for both the near and far future, indicating that the change in temperature had a stronger impact on Yw than the change in precipitation. Similarly, the relative changes in Yn and Yw were comparable (Table 3).

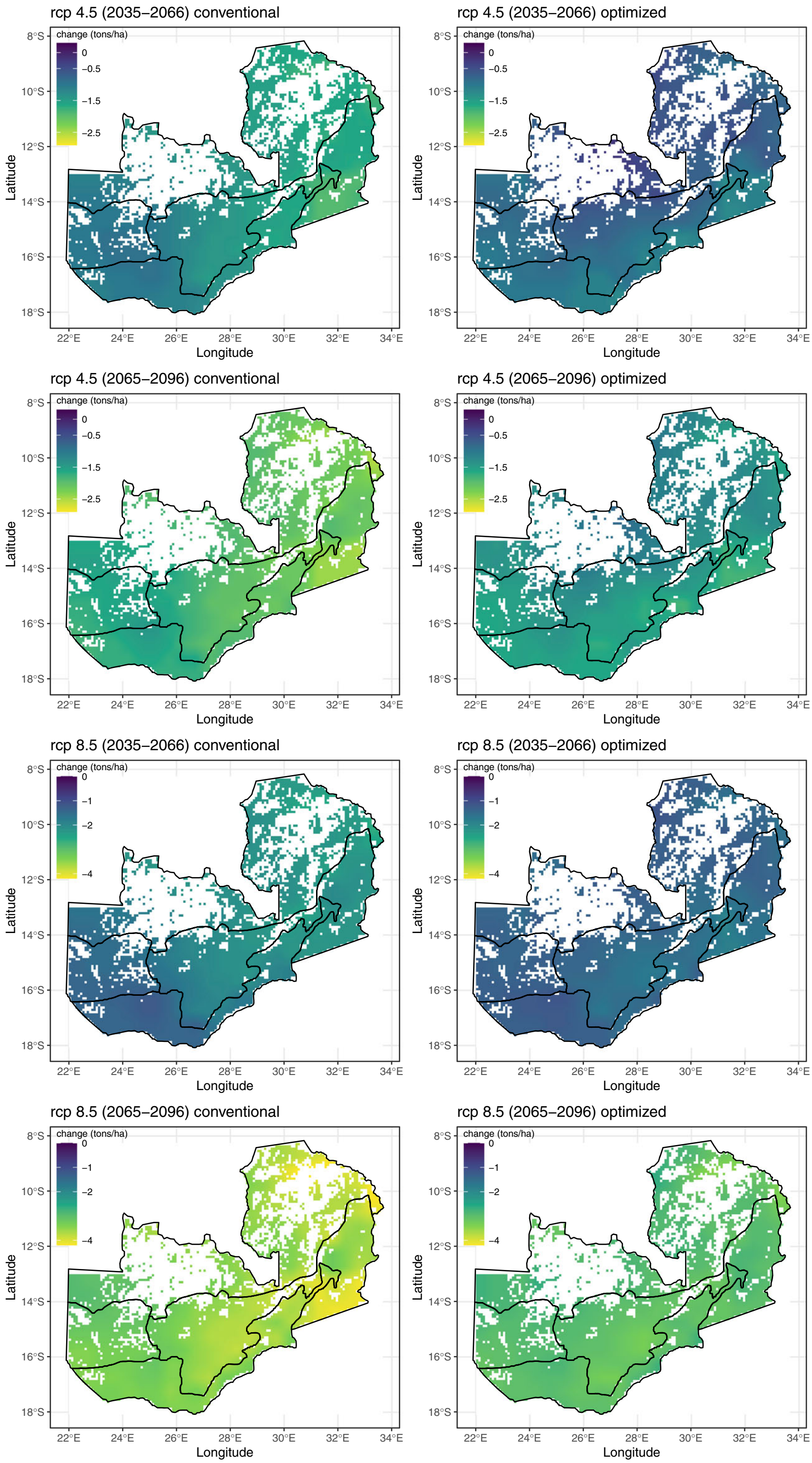
3.2.3 Mitigating negative impacts of climate change by optimal crop management

Figure 4 gives projections of Yw maize yields under "conventional management," consisting of a fixed planting date and variety (left) against "optimized management" consisting of optimized planting dates and varieties (right). Optimal management had a positive impact on maize yields under climate change. With conventional management in RCP 4.5, maize yield declined down to 1.4 ton/ha (15%) in the near future and down to 1.9 ton/ha (21%) in the far future. Under optimized management for the same RCP scenario, the projected yield declined with 0.8 ton/ha (8%) in the near future and with 1.3 ton/ha (14%) in the far future (Table 3). Under conventional management in RCP 8.5, a yield decline of 1.9 ton/ha (21%) in the near future and 3.5 ton/ha (37%) in the far future was shown for Yw (Table 3). However, optimizing management for the same RCP scenario, we generally have a yield decline of 1.4 ton/ha (15%) in the near future and 2.9 tons/ha (31%) in the far future.

The relative changes in Yn due to climate change were comparable to Yw. Under conventional management, the average yield declined in the near future by 0.7 tons/ha (16%) in RCP 4.5 and 1.0 tons/ha (22%) in RCP 8.5. For the far future, the yield declined with 1.1 tons/ha (22%) and 2.0 tons/ha (41%) respectively. However, optimizing management mitigated the decline in Yn by increasing yields except for the RCP 8.5 scenario in the far future (Table 3). For instance, there was an increase of 0.2 tons/ha (6%) for RCP 4.5 and 0.02 tons/ha (2%) for RCP 8.5 in the near future. In the far future, optimizing management increased Yn in RCP 4.5 by 0.1 tons/ha (3%) whereas in RCP 8.5 the yield decreased by 0.6 tons/ha (12%) (Table 3). The difference between the relative yield change under conventional and optimized management showed that management measures could avoid the climate-induced yield decline by 6-29% for both Yw and Yn.

Table 3 Summary statistics on the expected absolute and relative changes in maize yield change in the near future (2035-2066) and far future (2065-2096) compared to the reference period (1971-2001) at country level

Index	RCP	Mean	Standard deviation	Minimum	Maximum	Relative mean
		tons·ha^{-1}				
Potential yield	RCP 4.5 (near future)	-1.4	0.23	-1	-2.3	-15%
	RCP 4.5 (far future)	-1.9	0.23	-1.5	-3	-20%
	RCP 8.5 (near future)	-2.0	0.29	-1.4	-3.2	-21%
	RCP 8.5 (far future)	-3.5	0.34	-2.6	-5	-36%
Water limited (current conventional management)	RCP 4.5 (near future)	-1.4	0.29	-0.3	-2.3	-15%
	RCP 4.5 (far future)	-1.9	0.27	-0.9	-3	-21%
	RCP 8.5 (near future)	-1.9	0.39	-0.5	-3.2	-21%
	RCP 8.5 (far future)	-3.5	0.37	-1.9	-5	-37%
Water limited (optimized management)	RCP 4.5 (near future)	-0.8	0.28	-1.5	0.3	-8%
	RCP 4.5 (far future)	-1.3	0.28	-0.1	-2.2	-14%
	RCP 8.5 (near future)	-1.4	0.24	-1.9	-2.2	-15%
	RCP 8.5 (far future)	-2.9	0.32	-0.9	-4.2	-31%
Water and Nitrogen limited (current conventional management)	RCP 4.5 (near future)	-0.7	0.59	-1.4	1.4	-16%
	RCP 4.5 (far future)	-1.1	0.67	-1.7	1.6	-22%
	RCP 8.5 (near future)	-1	0.65	-1.9	1.5	-22%
	RCP 8.5 (far future)	-2	0.68	-2.8	2	-41%
Water and Nitrogen limited (Optimized management)	RCP 4.5 (near future)	0.2	0.46	-0.3	2.4	6%
	RCP 4.5 (far future)	0.1	0.46	-0.5	2.5	3%
	RCP 8.5 (near future)	0.02	0.44	-0.5	2.4	2%
	RCP 8.5 (far future)	-0.6	0.5	-1.2	2.1	-12%


rcp 4.5 (2035–2066) conventional
rcp 4.5 (2035–2066) optimized
rcp 4.5 (2065–2096) conventional
rcp 4.5 (2065–2096) optimized
change (tons/ha)
0
−0.5
−1.5
−2.5
rcp 8.5 (2035–2066) conventional
rcp 8.5 (2035–2066) optimized
rcp 8.5 (2065–2096) conventional
rcp 8.5 (2065–2096) optimized
change (tons/ha)
0
−1
−2
−4
Latitude
8°S
10°S
12°S
14°S
16°S
18°S
Longitude
22°E
24°E
26°E
28°E
30°E
32°E
34°E

◀ **Fig. 4** Predicted spatial variation in the changes in water-limited maize yields in 2035-2066 and 2065-2096 under climate scenarios RCP 4.5 and RCP 8.5 under conventional management (left column) and under optimized management (right column)

Figure 5 shows that the best variety option for the western and southern region includes the use of relatively early maturing varieties (90-120 days) or those varieties with Tsum values slightly above average (variety 3 in Table 1). In these regions, the optimal variety had Tsum values ranging between 1471 and 1871 (Variety 1-5), while the rest of the country was best suited with a variety that has a Tsum around 2071 (Variety 7). Figure 6 shows the suitable planting date for each region in the near and far future for both RCP 4.5 and 8.5. Suitable planting dates ranged from late November to mid-December except for the RCP 8.5 scenario in the far future. For the southern and western regions, suitable planting dates started around 27th November, while the maize in the other regions should be planted between 7th and 17th December. Combining Figs. 5 and 6 shows that the western and southern regions were best suited for early maturing varieties planted early in the suitable growing season. The rest of the country, particularly in the northern region, was best suited for late-maturing varieties.

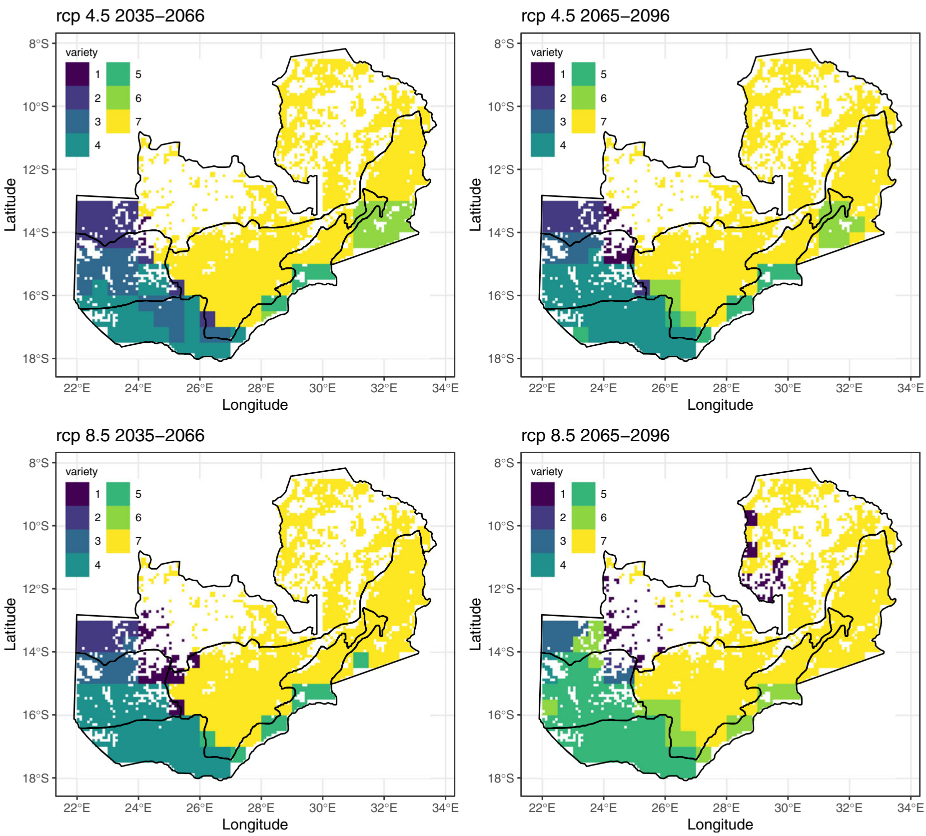


Fig. 5 Predicted spatial variation in the best-suited maize variety (see Table 1) in 2035-2066 and 2065-2096 under climate scenarios RCP 4.5 and RCP 8.5

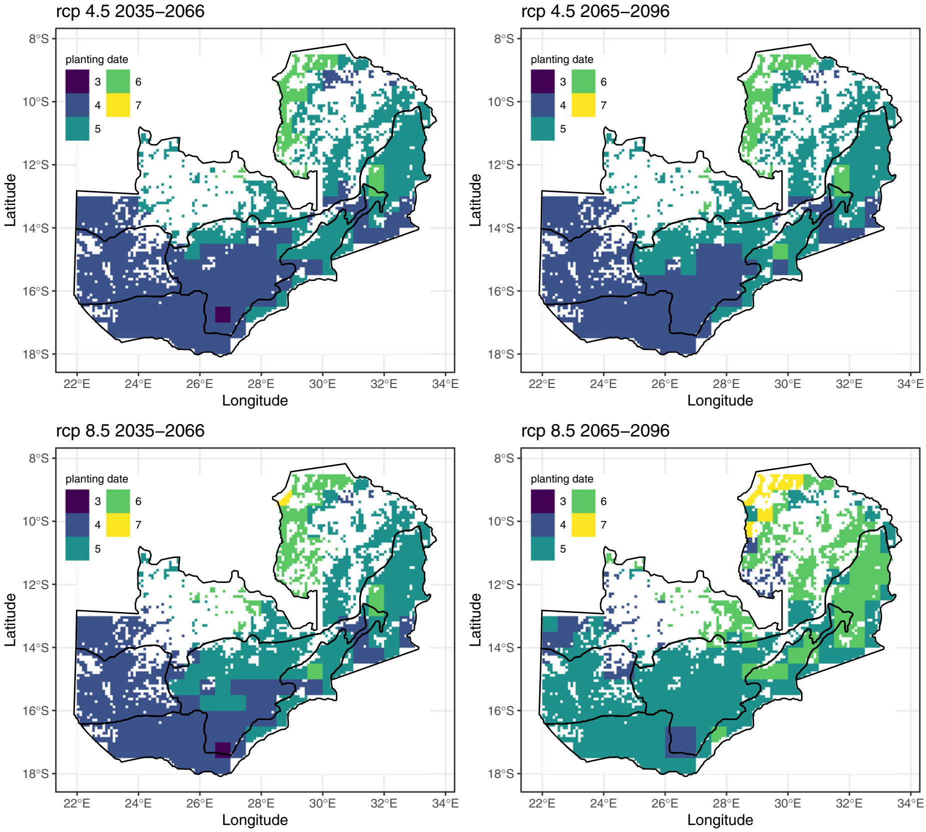


Fig. 6 Predicted spatial variation in the best-suited maize planting date (see Table 1) in 2035-2066 and 2065-2096 under climate scenarios RCP 4.5 and RCP 8.5

4 Discussion

4.1 Expected precipitation and temperature changes and its implications

Zambia's climate is projected to change mainly by a decrease in precipitation and an increase in temperature, especially in the south-western regions. These changes will negatively impact maize yields in both the short and long term. Fortunately, agronomic management such as appropriate nutrients, varieties, and planting dates has the potential to mitigate some of these negative impacts, and they can even reduce substantial parts of the existing yield gap. Translating this knowledge in manageable actions requires an agroecological approach accounting for location-specific farm and field properties.

Climate change will increase the number of days with temperatures above 30 °C and reduce the number of cooler days. This is consistent with findings at a global level (IPCC 2014) as well for southern Africa (Kruger and Shongwe 2004; New et al. 2006). Nevertheless, the spatial variation is huge with strong spatial patterns around the borders with Namibia, Botswana, Zimbabwe, and Mozambique (Fig. 1) due to the lower attitude and adiabatic descent leading to higher temperatures than the surrounding regions (New et al. 2006). Areas with high risks for heat-related stresses are likely to occur in Agroecological region I.

In addition, the annual average surface temperatures are also expected to increase, similar to the projected global trends (IPCC 2013; Lobell et al. 2011b) as well as regional trends in southern Africa (Maúre et al. 2018; New et al. 2006). However, the magnitude of change in Zambia is expected to be larger than the global average (Engelbrecht et al. 2015; IPCC 2014; Nikulin et al. 2018), a difference that can increase up to a factor of ten as shown by (Jain 2007) based on observations from 32 thirty-two meteorological stations over thirty years. A temperature increase will enhance potential evapotranspiration and corresponding crop water demand (Brüssow et al. 2019; Parent and Tardieu 2012), in particular for situations with water deficiencies (Déqué et al. 2017). Temperature changes are projected to be stronger westwards due to warming in the Indian ocean (Engelbrecht et al. 2015; Maúre et al. 2018).

Precipitation will decline in most of the regions except for the northern and north-western regions where convective precipitation increases due to changes in the synoptic-scale circulations for the eastern regions of southern Africa (Engelbrecht et al. 2009; Fauchereau et al. 2003; Pinto et al. 2016). Southern and western regions will be drier due to a reduction in both annual precipitation and wet days. Both drought and warmer temperatures increase the vulnerability of maize due to dry spells and heat stresses. The least relative change in wet days coupled with an increase in annual precipitation is expected in the northern region (AEZ III) implying an increase in occurrences of heavy precipitation events thus posing the risk of flooding or crop damage due to logging (Déqué et al. 2017). The overall reduction in the number of wet days is in line with earlier findings implying a shortening growing season, increased threat of crop failure, and livelihoods of smallholder farmers (Makondo and Thomas 2020; New et al. 2006). The reduction in rainfall might be small in magnitude, but generally, this has been consistent with multiple findings (Jain 2007; Maúre et al. 2018; New et al. 2006; Pinto et al. 2016). Such an occurrence increases the risk of crop failure due to either lack or too much water in the south-western and north-western regions respectively.

4.2 Expected climate change impacts on maize yield

The simulated rainfed (Yw) maize yield is 9.5±1.6 tons·ha-^{1} which is in the same order of magnitude as those presented in the Global Yield Gap and Water Productivity Atlas. This yield estimate is based on good agronomic management comprised of suitable varieties and planting dates and appropriate fertilization, pest, and disease control. However, in reality, the actual yields are about 80% lower due to conventional management limitations. Commonly, smallholder farmers use subjective estimations to select the planting date and maize varieties based on perceived rain patterns or growing season (Brüssow et al. 2019) and blanket fertilization strategies (Njoroge et al. 2017; Xu et al. 2009). As a consequence, actual yields (2-3 tons/ha) are significantly lower than the potentially achievable rainfed yield.

Maize yields may decline due to climatic-induced changes in temperature and rainfall. Higher CO_2 levels are not expected to have much of an influence on maize given its a C4 plant type (Leakey 2009). The decline in yield is therefore largely controlled by the change in temperature. The projected yield reduction trend is aligned with the projected global trends and other regional studies (Lobell and Field 2007; Zinyengere et al. 2013), and strongly determined by the daily maximum temperature given its influence on the phenological development of the maize. Higher temperatures reduce the time for photosynthesis and grain filling which in turn reduces yield (Craufurd and Wheeler 2009; Liu et al. 2013; Liu et al. 2012). During the growing season, temperatures in the far future could increase from the reference temperature of 24 °C by up to 3 to 5 °C for RCP 4.5 and RCP 8.5 respectively.

There are various suggested thresholds beyond which maize yield decline, varying from 29 °C (Schlenker and Roberts 2009), 30 °C (Lobell et al. 2011a), 36 °C (Sánchez et al. 2014), and even 40 °C (Birch et al. 1998). With the expected increase in the number of hot days (with temperatures above 30 °C), it is clear that the potential yields decline, in particular when the temperature exceeds the 36 °C. The expected yield decline is relatively largest in high-yielding areas (Schlenker and Lobell 2010). The projected increase in temperature had a relatively stronger contribution for the decrease in maize yields than changes in rainfall. Since the annual rainfall exceeds 700 mm in most of Zambia, the projected precipitation decrease has only a slight impact on crop production (Liu et al. 2012). Knowing that future rainfall shows high spatial and temporal variability, especially in the semi-arid regions, maize yield might show more drastic negative effects than those derived from temperature changes only.

Maize Yw growing under conventional management indicates that yield reduction takes an eastward trend similar to Yp. This trend of yield change coupled with the precipitation analyses indicates that most of the future maize yield reduction in Zambia can be largely attributed to a change in temperature. This increase in temperature would also increase water demand by crops (Brüssow et al. 2019). Hence, the threat of crop failure increases especially when the increase in temperature is not compensated with an increase in precipitation (Déqué et al. 2017). The importance of temperature for crop yield is supported by previous studies showing that temperature has a stronger influence on yields than precipitation (Lobell and Field 2007; Schlenker and Lobell 2010). These findings indicate that adaptation activities should include significant efforts to breed maize varieties that are heat and drought tolerant due to expected increases in temperature and changes in rainfall.

There is a difference of approximately 5 tons/ha between Yn and Yw, indicating that current yields are limited by nutrient availability. Other studies have indeed emphasized that nutrient management will complement adaptation efforts (Schlenker and Lobell 2010). Yn will decline by 16-41% compared to 15-36% reduction expected for Yp and Yw. The slightly higher reduction in Yn is due to a climate-induced reduction in NUE given that more rainfall and higher temperatures enhance risks for N losses via volatilization and leaching (Falconnier et al. 2020). Furthermore, water deficits coupled with increased temperatures lead to lower nitrogen uptake and crop yield (Liang et al. 2018). Optimizing management practices including fertilizer application has the potential to mitigate the impacts of climate change on maize yields. For instance, split fertilizer application and manure application can improve both NUE and yields (Falconnier et al. 2020; Liang et al. 2018). Even though the absolute magnitude of Yn, Yw, and Yp may be highly uncertain at local scale, the simulated relative changes in crop yield potentials due to climate change as well as the impact of mitigation measures are still valid (Zinyengere et al. 2013).

4.3 Uncertainty in predicted climate change impacts

Like any crop model, WOFOST embodies various assumptions and simplifications, such as the absence of processes quantifying the ability of plants to adapt to low resource conditions by modifying its morphology and physiology. WOFOST may therefore overestimate the drought effects. Sowing date variations or occurrence of re-sowing in response to droughts may occur at a regional scale. However, since no information on these phenomena is available, an average sowing date per grid box is assumed. In addition, the projected magnitudes of changes in climatic variables are subject to uncertainties arising from the standard structure of GCMs, climate change scenarios, and initial conditions (Woldemeskel et al. 2014). Therefore, to reduce these uncertainties, we used five GCMs ensemble averages to quantify the changes (Dale et al. 2017).

Furthermore, the accuracy of predicted changes in water-limited crop yields in response to climate change, especially an increasing temperature, depends mainly on the accuracy in which crop growth models include the interacting effects of drought, rising temperatures, and CO_2 fertilization. This refers to the description of the yield-enhancing effects of CO_2 fertilization that may dampen the negative impacts of rising temperatures and drought or the way in which water availability dampens the effect of high temperatures. Insight in the accuracy has to come from experimental field evidence as highlighted by Silva and Giller (2021). They illustrate this point for coffee, where research under controlled conditions suggests impacts at temperatures above 33 °C, whereas high yields are observed in irrigated areas where maximum temperatures exceeding 35 °C up to 39 °C. Fortunately, cereals, including maize, are much more intensively researched than other crops, and hence, the experimental evidence underpinning the model parameterization for maize in WOFOST is quite high. Nevertheless, uncertainties in interacting effects of water, temperature, and CO_2 are still topics of research.

Another uncertainty is related to the aggregation of the variation in management, climate and soil properties by using a 0.5 degrees spatial resolution for modeling, implying that regional variation at higher resolution is not accounted for. This generalization might have implications on the magnitude of change in yields; however, the relative changes across scenarios are unaffected. As a consequence, the current data availability does not yet allow us to predict future conditions at the degree of spatial, temporal, and probabilistic precision which is needed for locally adapted decisions making (Nissan et al. 2019).

4.4 Potential to reduce climate change impacts by management

This study focuses on options to increase maize yields by improving management (adapting planting dates and crop varieties) that mitigate climate change impacts, measures that have also been identified as a promising way to improve wheat yields in Australia (Richards et al. 2014). There is also the option to change the cropping system to other more heat and drought tolerant crops. However, as considering the expected climate change, there is still enough room to improve the maize yield. Furthermore, switching from maize as a staple food to an another may encounter societal difficulties.

Optimizing management by appropriate planting date and variety reduced the magnitude of yield decline for both Yw and Yn in the near and far future by ca 6-29% as compared to conventional management, being comparable to findings in a field survey (Karapinar and Özertan 2020). Maize grain yields have increased by 4% due to changes in sowing date and 13-38% due to change in cultivar (Liu et al. 2013) and by 7.1–57.2% by a change in both sowing data and cultivars during the period 1981–2007 (Zhao et al. 2015) .

The thermal attributes of varieties was the main differences in this context, and it is worth noting that varieties in reality vary on more than thermal attributes. A slightly better improvement was predicted for Yn than for Yw, even causing an increases in yields compared to the reference period, despite climate change. This is probably due to synergistic interactions between the shift in planting dates and the date of fertilization (Johnston and Bruulsema 2014).

Western and southern Zambia are expected to have high temperature increase coupled with less rainfall; this means we need to plant early maturing drought tolerant varieties and select suitable planting dates. Optimizing management is beneficial, cheap, and easy to implement since it is incremental adaptation and avoids huge financial investments (Challinor et al. 2014; Karapinar and Özertan 2020; Lobell et al. 2011b). However, adopting these "cheap" technologies will require an enabling environment based on a systems approach to ensure that farmers access the suitable varieties in good time especially for the resource-constrained farmer under the Zambian government input support program (Arslan et al. 2015). Furthermore, adopting these options is subject to a farmer's risk perception of changes in climate; therefore, there is a need for sensitization (Brüssow et al. 2019). Various studies have highlighted the benefits of variety choices and planting dates as adaptation strategies (Araya et al. 2020). However, it is important to note that there exists a time lag between development, dissemination, and acceptance of improved varieties and it is thus important to prioritize research in developing improved varieties (Cairns et al. 2013).

Based on our results, the yield gap between Yw and Yn is estimated at 50%, being on average near 5 tons/ha, while the yield gap atlas calculates the yield gap between Yw and Ya at 70-80% translating to 9-10 tons/ha. The gap between Yw and Yn is due to nutrient limitation with N as a surrogate, while the gap between Yw and Ya is due to nutrient limitations, weeds, pests, diseases, and pollutants (Van Ittersum et al. 2013). It is, therefore, important to increase yields, as a first priority before we address climate change adaptation (Crespo et al. 2011). Our findings highlight that nutrient limitation plays a key role in the current yield gaps. This can also be seen from the N requirements of maize at a target yield of, e.g. 8 tons/ha (Lobell et al. 2009; Sadras et al. 2015). A target yield of 8 tons/ha equals a N fertilizer demand of 240 kg N/ha (assuming a N content of 1.5% (Yang et al. 2012) and a NUE of 50%), resulting in a N demand exceeding the recommended N input of 112 kg N/ha. When we aim for a yield of 8 tons/ha, and assume a slightly higher potential NUE of 60% by proper fertilizer management including appropriate additions of phosphorus and zinc that often limit crop yields in Zambia (Yerokun 2008; Yerokun and Chirwa 2014), an N input of 200 kg N/ha would be recommended. Conclusively, increasing the actual yields will require a holistic farm system approach considering various aspects of agronomic management including land preparation, pest and disease control, and weed management.

5 Conclusions

Climate-induced changes in temperature, precipitation, and corresponding impacts on maize yields in Zambia have been quantified. Results show that without countermeasures, maize yields will decline by 20-40% in particular for the southern and western regions. Currently, maize yield gaps due to nutrient limitations are projected to widen due to climate change if no counter measures are introduced. Improved agronomic and nutrient management can mitigate the climate-induced negative impacts on crop yield, eventually improving crop yield in all regions across Zambia. A closer look indicates that the change in temperature has a stronger negative impact than the change in precipitation, although this varied across Zambia. The southern and western regions should focus on measures addressing the higher temperature and reduced precipitation whereas the northern region struggles with higher temperature levels as well as high precipitation. Maize varieties that are tolerant for higher temperatures are always beneficial. Fertilizer strategies improving NUE will boost crop production, avoiding some of the negative impact of climate change. More attention to earlier onsets of the rain season might be important for further optimization of maize production. This model study confirms that via optimum agronomic management the actual crop yields can be improved substantially, thereby closing the existing yield gap and mitigating negative climate-induced impacts.

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Data availability The climate and crop simulation data are readily available on request.

Code availability The custom code of WOFOST in C can be accessed on https://github.com/isupit/wofost_c

Declarations

Conflict of interest The authors declare that there are no conflicts of interest.

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