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 is currently lacking for Zambia. Using five Global Circulation models and the WOFOST crop model, we assessed expected climate change and the 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 two future periods (i.e. near future: 2035–2066 and far future: 2065–2096) in comparison with a reference period (1971–2001). The average surface temperature and summer 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 while the number of wet days decline everywhere, indicating a shortening 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 ca 15–20% in the near future and from ca 20–40% in the far future, mainly due to the expected temperature increases. Optimizing management by adjusting planting dates and maize varieties can counteract these impacts by 6–29%. Quantitatively, the existing gaps between water limited yields and nutrient limited maize yields are substantially larger than the expected yield decline due to climate change. Improved nutrient management is therefore crucial to avoid crop yield decline and might even increase crop yields in Zambia.

1 Introduction

Rainfed agriculture in Sub-Saharan Africa (SSA) is characterised by threats of crop failure due to multiple stresses with the most important ones being climatic conditions and nutrient deficiencies (Love et al., 2006). 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; Tesfaye et al., 2015). In Zambia, as in many countries in SSA, maize is commonly grown by smallholder farmers and the production has a strong influence on both national economy and household food security (Arslan et al., 2015; Schlenker and Lobell, 2010). In 2017 maize was harvested from approximately 1.4 million out of the 3.8 million hectares of arable land (Faostat, 2020). Most of the smallholder farmers are dependent on rainfed agriculture (Love et al., 2006).

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, changes in temperature and precipitation have been shown to impact both target and actual maize yields (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, climate change induced changes in both 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; Tesfaye et al., 2015). Understanding maize yield responses to climatic changes and 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 on maize yields is useful for at least two reasons. Firstly, this generates region specific knowledge for policy and adaptation measures or priorities in relation to crop and climate change (Challinor et al., 2009; Leng, 2017). For instance, agronomic management such as planting dates, varieties selection, irrigation and residue management have been evaluated as climate change adaptation measures in specific regions (Brüssow et al., 2019; Challinor et al., 2014; Karapinar and Özertan, 2020; Shi et al., 2019). Secondly, insight in the impacts of climate change on water limited yield is also relevant as it is often used to derive rainfed target yield levels (mostly set at 80% of Yw) for use in fertilizer recommendations (Sherene et al., 2016). Recommended fertilizer doses are usually designed to fulfil crop nutrient requirement to reach a target yield given critical soil nutrient thresholds. Using the target yield as driver of the required nutrient dose results often in more precise and economic optimum fertilizer practices (Sandal et al., 2008; Singh et al., 2004) and avoids adverse impacts on the environment due to overfertilization (Xu et al., 2013). Accurate insight into target yields 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). Robust fertilization recommendations ensuring both crop production and environmental quality requires therefore spatially explicit insights in the evolution of water-limited yields.

In addition to nutrient management, it is also important to evaluate the possible adaptation options such as altering planting dates, 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; Knox et al., 2012; Shi et al., 2019). Temperatures and precipitation changes in the short-term can be mitigated by adjusting planting dates and switching varieties as adaption (Liu et al., 2018). For instance, historical maize yield increased by altering both planting dates and varieties of maize in China (Zhao et al., 2015).

Currently, there has been little insight in the mitigative potential of agronomic crop and fertilizer management under expected climate change in Zambia. Furthermore, the insights into the mitigative potential of management rarely considered optimizing combinations of various management options. These insights are critical because the response of crops to interaction of climate change and agronomic management varies with location (Carter et al., 2018; Wineman and Crawford, 2017). Therefore, we assessed the projected changes in maize yields in Zambia due to climate change and evaluated the maize yield response to agronomic management using the best combination of varieties and planting dates. These insights provides a basis to design sustainable management strategies enabling farmers to cope with upcoming climatic changes.

2 Methods

This study takes a modelling approach to analyse 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 referred to as Relative Concentration Pathways (RCPs) depicting the moderate and worst case scenario. Impacts for yield are 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 relationship between maize yields and climate at country level, assuming that the entire country grows maize.

2.1 Study area

Zambia is located in southern Africa between longitudes 21°E to 34°E and latitude 8°S and 18°S (Libanda et al., 2019). The country is approximately 725615 km^2 characterised with a subtropical climate and average annual rainfall ranging between 700–1200 mm (Jain, 2007). Based on climate and soil characteristics Zambia is divided into three major agroecological regions called AER I, II and III (Chikowo, 2016; Veldkamp, 1987). The climatic data used in this study had 0.5° × 0.5° spatial resolution (Hempel et al., 2013) therefore, the country was divided into grid cells instead of agroecological regions. Both climate and maize yields were analysed for each grid cell and the corresponding dominant soil types were derived from soil texture maps (Hengl et al., 2015). The soil textures were subsequently aggregated into three generalized default soil types used in the WOrld FOod STudies (WOFOST) crop model. i.e. coarse, medium and medium fine textured soils.

2.2 Climate projections

Bias-corrected data from five selected Global Circulation Models (GCMs) in the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) 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 were analysed for temperature and precipitation indices using Climate Data Operators (Schulzweida, 2018). The indices analysed included average surface temperature; summer days; precipitation; and wet days. To analyse the change in an index, the difference was calculated between the reference period and a future time period.

2.3 Maize yield modelling

2.3.1 Maize yield analysis

The impact of climate change, current conventional management and optimized management on maize yields were evaluated. Firstly 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). Secondly, to analyse the impact of changes in precipitation, we simulated water limited rainfed (Yw) maize production while assuming that nutrients are not limiting. Thirdly to gain insights into the effects of current management on maize yields, the water- and nitrogen-limited (Yn) maize yields were simulated. We focused on nitrogen limitation as a proxy for management. Finally, we explored the impact of optimizing management (varieties and planting dates) on water limited (rainfed) maize yields as proxy to climate change adaptation. To optimize varieties and planting dates, we evaluated 77 combinations of varieties and planting dates (Table 1). Thereafter, the optimal combination of variety and planting date was identified by evaluating which of the 77 combination has the highest mean yield; lowest standard deviation and the highest lower (25th) quartile.

Table 1
Details on varieties 1–11 (left column) and planting date 1–7 (right column) used in the optimization simulation.

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		

2.3.2 WOFOST model

WOFOST was used to simulate maize production in Zambia as it has been used in previous studies in SSA including the Global yield gap atlas (http://www.yieldgap.org/) (Wolf et al., 2015). Crop growth and production were simulated on a daily timestep during a growing season as determined by crop type, soils, hydrologic conditions and weather (Van Diepen et al., 1989). The 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). Phenological development and respiration are mainly determined by the temperature while CO_2 assimilation is determined by absorbed radiation and photosynthesis-light response curves. Partitioning of assimilates to various storage organs are based on static partitioning tables as a function of development stage of the crop.

2.3.3 Model Parameterization

WOFOST was driven 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 WOFOST 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 neither limiting by applying sufficient amounts of both elements. The Nitrogen Use Efficiency (NUE) was set at 50% based on the global estimation of NUE at ca 47% (Lassaletta et al., 2014). We use the global NUE because we currently lack a quantified average NUE for Zambia and the estimates of NUE in SSA are more than 100% due to nutrient mining (Edmonds et al., 2009; Pasley et al., 2020).

A standard tropical maize variety (maiz.w41) in WOFOST was modified by successively adjusting the Temperature sums (Tsum1 and Tsum2) in intervals of 100 degrees thus creating multiple maize varieties in Zambia (Table 1). Tsum 1 controls degree days for the period between emergence and anthesis while Tsum 2 determines the degree days between anthesis and maturity. Maize planting dates in Zambia currently fall between 20th November and 5 December (Chikowo, 2016), in this study we explore multiple 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: This management approach is characterized by a fixed planting date (26th November) and a common average-performing maize variety (Tsum = 1671) over the whole country.
b. Optimized management: This management approach is characterized by multiple combinations of 11 varieties assessed over 7 planting dates. The resulting 77 combinations are applied across the country after which the best option is selected for each grid cell.

Table 1: Details on varieties 1–11 (left column) and planting date 1–7 (right column) used in the optimization simulation

3 Results

3.1 Climate indicators

3.1.1 Temperature

Given climate change, 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 affect maize growth and yield. When both future climate scenarios are compared, it is evident that the magnitude of temperature changes increases over time. The magnitude of increase is stronger in the far future and in the severe climate change scenario (RCP8.5). The spatial distribution of the expected changes are similar in both RCP scenarios. The increase in summer days (days above 30°C) is stronger in the southern and western parts of the country (Fig. 1). Compared to the reference period, the near future scenarios are 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 increases on an east-west gradient, with an increase up to 2.6°C in the near future and up to 4.6°C in the far future. During the maize growing season, projected temperature increases in the October-December (OND) period for RCP 4.5 and 8.5 are 2°C and 3°C (near future) and 3°C and 5°C (far future). Further projections for the period January-March (JFM), 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

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				

Index	Time period	Absolute				Relative change			
		Minimum	Mean	Maximum	Standard deviation	Minimum	Mean	Maximum	Standard deviation
	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

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

Figure 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)

3.1.2 Precipitation

Over the whole country, the number of wet days are likely to decline (Table 2). In the near future, the number of wet days 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 is stronger towards the south-west regions. On average, both RCP scenarios show a general reduction in the annual precipitation but showed an increase in the northern regions and a reduction in the southern-western regions (Fig. 2 and Table 2). In future projections, there is a reduction of precipitation in the onset of rain season (OND) and increase towards end of the season (JFM) (Data not shown here).

Figure 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)

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 modelled average Yw is 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 the water limited and water- and nutrient- limited yield is 4.8 tons/ha. Currently the lowest yields are found in the western and southern parts of the country, being part of agroecological region I, particularly around the valleys (Fig. 3). The modelled Yn is almost 2 ton/ha higher than average actual yield (Ya), which vary between 2–3 ton/ha (as estimated by GYGA).

Figure 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 average maize Yp decline 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 15–21% of the maize 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. The yield decline increases from the west to the east. For both RCPs, the decline in Yw is equal to the decline in Yp for both near and far future, indicating that the change in Yw is controlled by the expected change in temperature rather than the change in precipitation. Similarly, the relative change in Yn and Yw is comparable, but the absolute decline in Yn is approximately half the decline in Yw (Table 3), since the average Yn in the reference period is on average twice as low as Yw.

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%

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

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 is expected 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.

Figure 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).

The relative changes in water- and nutrient limited yield (Yn) due to climate change are comparable to Yw. Under conventional management, the average yield declines in the near future by 0.7 (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 (22%) and 2.0 tons/ha (41%) respectively. However, optimizing management avoids the Yn yield decline by increasing yields except for the RCP 8.5 scenario in the far future (Table 3). For instance, there is an increase of 0.2 (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 increases the Yn in RCP 4.5 by 0.1 tons/ha (3%) whereas in RCP 8.5 the yield decreases by 0.6 tons/ha (12%) (Table 3). The difference between the relative yield change under conventional and optimized management indicates that selecting the right management could avoid the climate induced yield decline by approximately 6–29% for both Yw and Yn.

Figure 5 shows that the best variety option for the western and southern region includes the use of relatively early maturing varieties with the low Tsums or the use of varieties with Tsum values slightly above average (variety 3 in Table 1). In these regions the optimal variety have Tsum values ranging between 1471 and 1871 (Variety 1–5) while the rest of the country is best suited with a variety that has a Tsum value around 2071 (Variety 7). Figure 6 shows the suitable planting date for each region in near and far future for both RCP 4.5 and 8.5. Suitable planting dates range from late November to mid-December in all time periods and scenarios 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 – 17th December. Combining Figs. 5 and 6 indicates that the western and southern regions are best suited with early maturing varieties planted early in the rain season. The rest of the country particularly in the northern region are best suited for late maturing varieties that are planted later in the growing season.

Figure 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.

Figure 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, management has the potential to mitigate most of these negative impacts and can even close substantial part of the existing yield gap.

Climate change will increase the number of days with temperatures above 30°C and simultaneously reducing the number of cooler days. This is consistent with findings at a global level (IPCC, 2014) and in southern Africa (Kruger and Shongwe, 2004; New et al., 2006). Despite this trend, the spatial variation is huge with strong spatial pattern around the borders with Namibia, Botswana, Zimbabwe and Mozambique (Fig. 1) as consistently observed in previous studies (New et al., 2006). This region is commonly associated with the presence of valleys and due to the lower attitude and adiabatic descent in these valleys, temperatures are likely to be warmer than the surrounding regions. Areas with high risks for heat related stresses are likely to occur in Agroecological region I.

In addition, the annual-average surface temperatures are 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). Analysing observed temperatures from thirty-two meteorological stations over thirty years (Jain, 2007) showed that temperature increase in Zambia were ten-times higher than both the average global temperature increase and even the projected increase for southern Africa. This increase in temperatures will enhance potential evapotranspiration and corresponding crop water demand (Brüssow et al., 2019; Parent and Tardieu, 2012), more so if the available precipitation is not sufficient to counter this demand (Déqué et al., 2017). Temperature changes are projected to be stronger westwards corresponding with the expected trend in the southwestern region of the southern African subcontinent 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 are characterized with a reduction in both annual precipitation and wet days indicating that these regions will be drier. The reduction in precipitation coupled with the strong increase in temperature in this region increases 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 $tons{\bullet}ha^{-1}$ which is in the same order of magnitude as those presented in the Global Yield Gap and Water Productivity Atlas (Available URL: www.yieldgap.org accessed on: 23/03/ 2020). 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 lower due to conventional management limitations with respect to varieties, planting dates, nutrient management and pests and diseases. Commonly, smallholder farmers use simple estimations to select the planting date; use generalized maize varieties and inappropriate fertilization strategies. As a consequence, actual yields (2–3 tons/ha) are significantly lower than the potentially achievable rainfed yield.

Maize yields are expected to decline due to climatic induced changes in temperature and rainfall. Apart from the management and environmental factors controlling the yield potential, temperature and CO_2 levels are assumed to be altered by climate change. Higher CO_2 levels are not expected to have much of an influence on maize given its a C4 plant type (Leakey, 2009).

Changes in yield are therefore largely controlled by changes in temperature. The estimated yield reduction matches perfectly with global trends and other regional studies (Lobell and Field, 2007). This is largely controlled by the daily maximum temperature due to its influence on the phenological development of the maize by reducing 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 for both RCPs could increase from the reference temperature of 24°C with about 3 to 5°C .

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 days with temperatures above 30°C, it is logical that the potential yield declines. The expected yield decline is relatively largest in high yielding areas (Schlenker and Lobell, 2010). Climate change had a similar impact on both Yp and Yw. This means that the projected increase in temperature is mainly responsible for the decrease in maize yields. Since the annual rainfall exceeds 700 mm in most of Zambia, the projected precipitation decrease has no or only a slight impact on crop production (Liu et al., 2012). However, for maize Yw under conventional management our analysis indicates that yield reduction takes an eastward trend similar to the 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 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 tolerant to increases in temperature.

There is a difference of approximately 5 tons/ha between Yn and Yw, indicating that there is currently nutrient limitation in Zambia. Other studies have 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 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).

4.3 Potential to reduce climate change impacts by management

Optimizing management by appropriate planting date and variety reduced the magnitude of yield decline for both water-limited yields and water- and nutrient limited yields 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). 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 earlier with early maturing variety 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). Various studies have highlighted the benefits of variety choices and planting dates as adaptation strategies (Araya et al., 2020).

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 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). Our findings and those of the yield gap atlas 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, being approximately 80% of the water limited yield, which is often used as a target value for farmers (Lobell et al., 2009; Sadras et al., 2015). Using this crop yield and an N content in harvested maize near 1.5% (Yang et al., 2012) this implies an N demand of 120 kg N/ha, being already higher than the blanket N recommendation input of 112 kg N/ha used in this study. Since we assumed an NUE of 50%, it is evident that N limits actual crop yield. When we aim for a yield of 8 tons/ha, and assume a slightly higher potential NUE of 60%, by proper management of all other nutrients including appropriate additions of phosphorus (P) and zinc (Zn) that often limit crop yields in Zambia (Yerokun, 2008; Yerokun and Chirwa, 2014), an N input of 200 kg N/ha would be recommended.

5 Conclusions

This paper analyzed the changes in temperature, precipitation and corresponding impacts on maize yields in Zambia. The findings show that without counter measures, maize yields will decline by 20–40% in the near to far future in particular the southern and western regions. Currently maize yield gaps due to nutrient limitations are estimated near 50% and this gap is projected to increase due to climate change. Comparatively, existing yield gaps due to nutrient limitations are larger than the yield decline expected due to climate change. This comparative analysis emphasizes the need for Zambia to close up the existing yield gaps attributed to nutrient management in the face of climate change. A closer look indicates that the change in temperature has a stronger negative impact on maize yields than the changes in precipitation. This impact is spatially different across Zambia, and hence, adaptation measures in the southern and western regions should focus on addressing temperature increases and precipitation reduction while the northern regions should focus on temperature and precipitation increases. Overall, this highlights the need for higher temperature tolerant maize varieties and adaptation measures that address temperature related changes. Optimizing management via planting dates and variety choices is evidently beneficial under changing climate. In addition, improving fertilizer application and nutrient use efficiencies could be part of optimizing management. With or without optimized agronomic management maize yields will decline, requiring a revision of current fertilizer recommendations driven by target crop yields. Future studies should focus on analyzing the occurrence of false starts in the rain season because of their importance in maize production. This study also shows that with optimum fertilizer management the actual crop yields can be improved substantially, mitigating any climate induced yield declines.

Declarations

Declarations

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Conflicts of interest/Competing interests: The authors declare that there are no conflicts of interest.

Availability of data and material: The climate and crop simulation data readily available on request.

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

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Figures

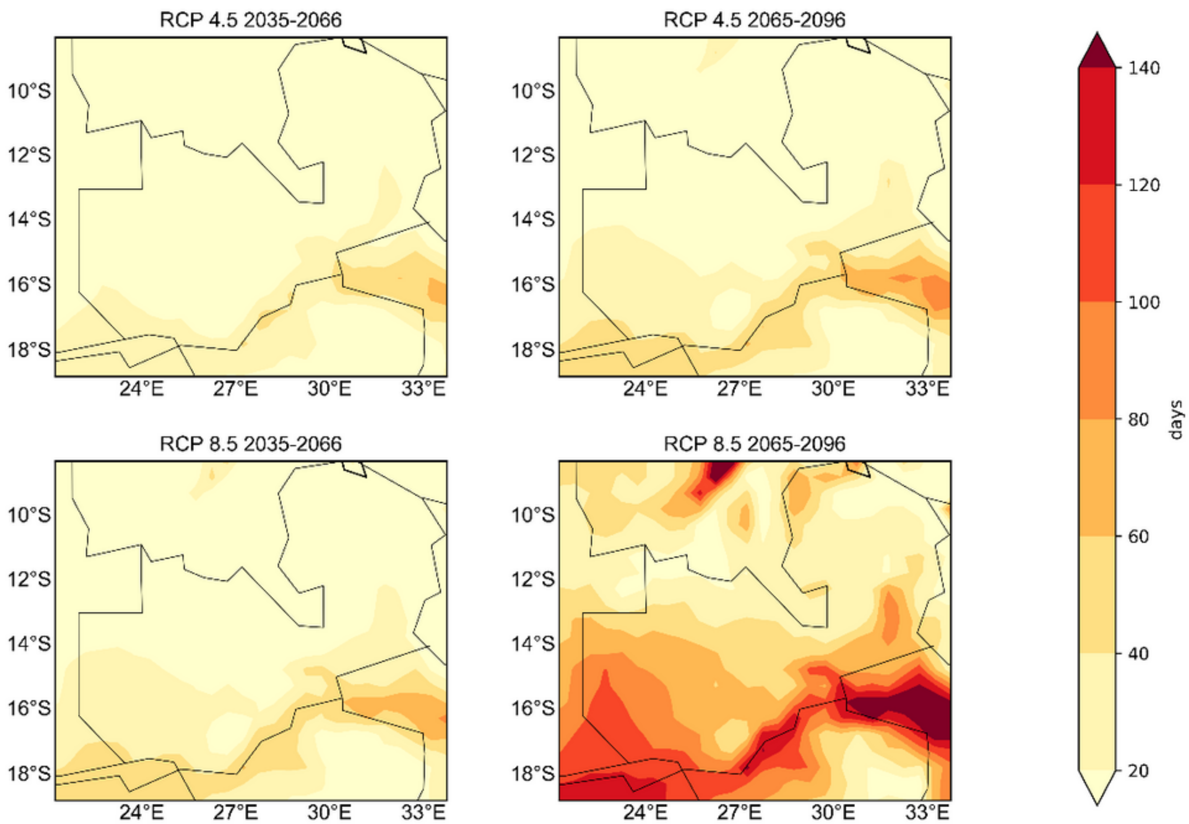

Figure 1

Projected relative change in summer days (above 30°C) as compared to the reference years (1971-2001)

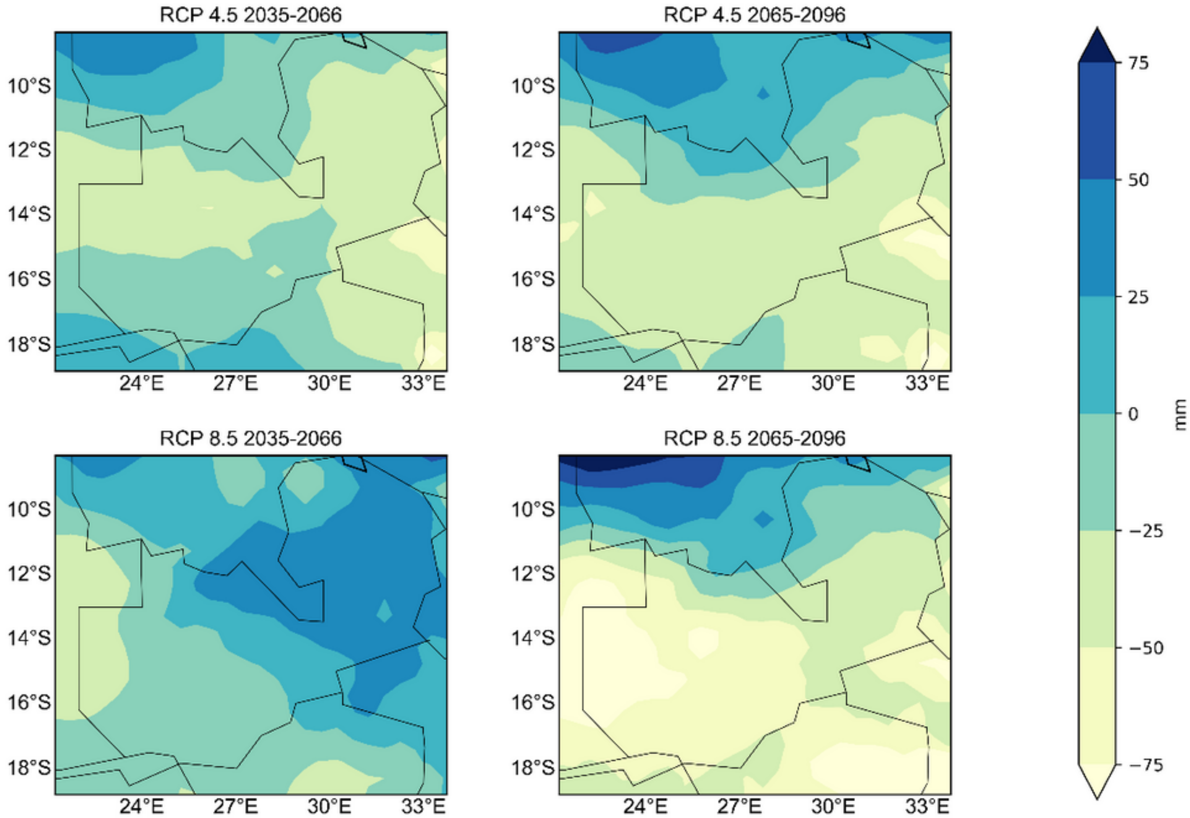

Figure 2

The projected relative change in average annual precipitation (mm•year-1) as compared to the reference years (1971-2001)

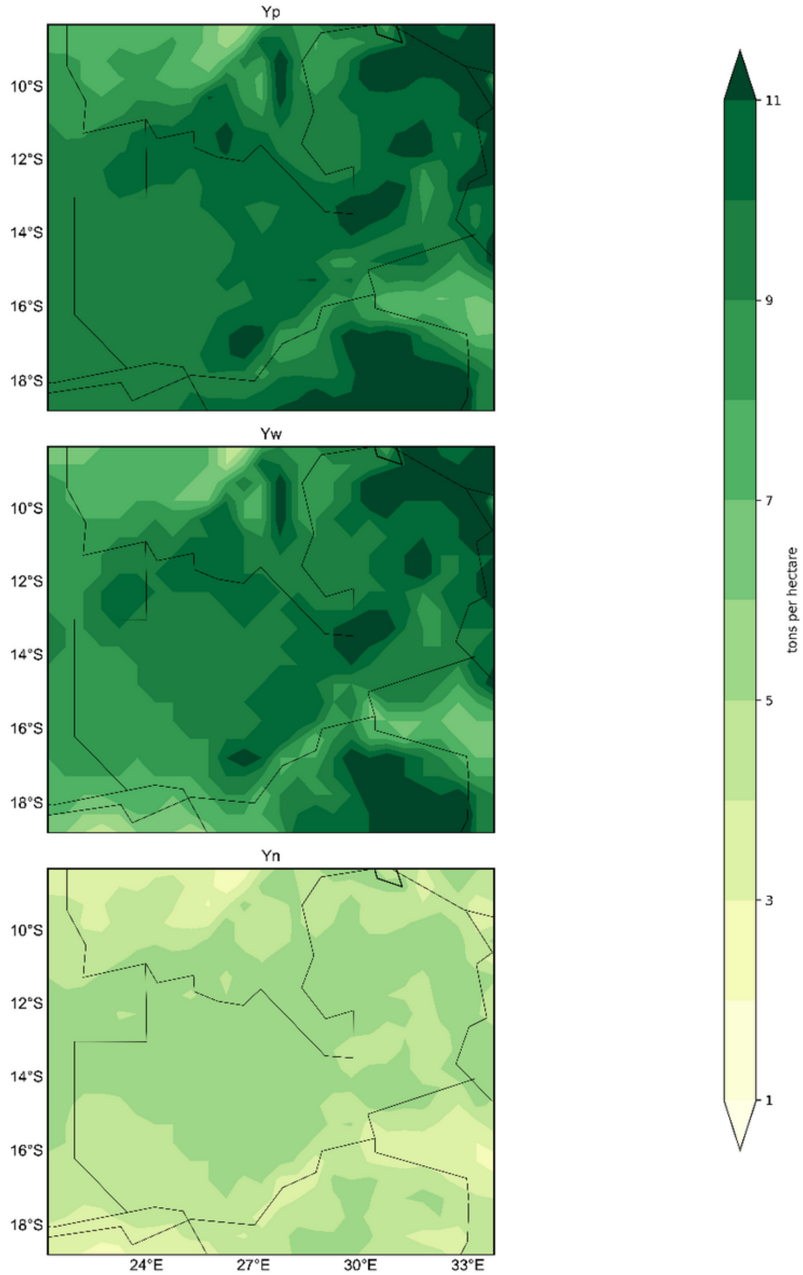

Figure 3

Spatial variation in simulated potential yields (Yp), water limited yields (Yw), and water- and nutrient limited yield (Yn) during the reference period (1971-2001)

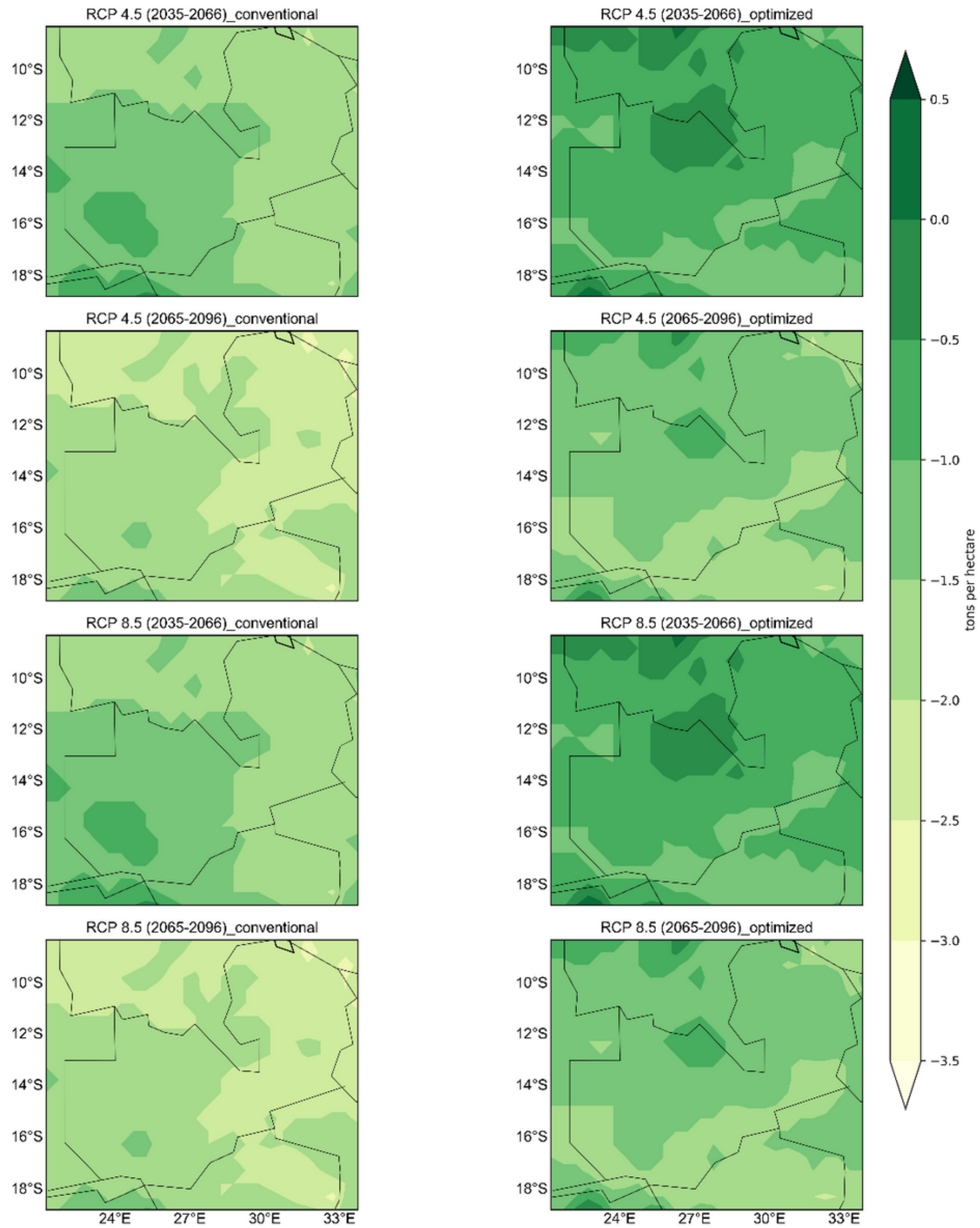

Figure 4

Projected change in the water limited maize yields under conventional management consisting of a fixed planting date and variety (left column) and under optimized management consisting of optimized planting dates and varieties (right column).

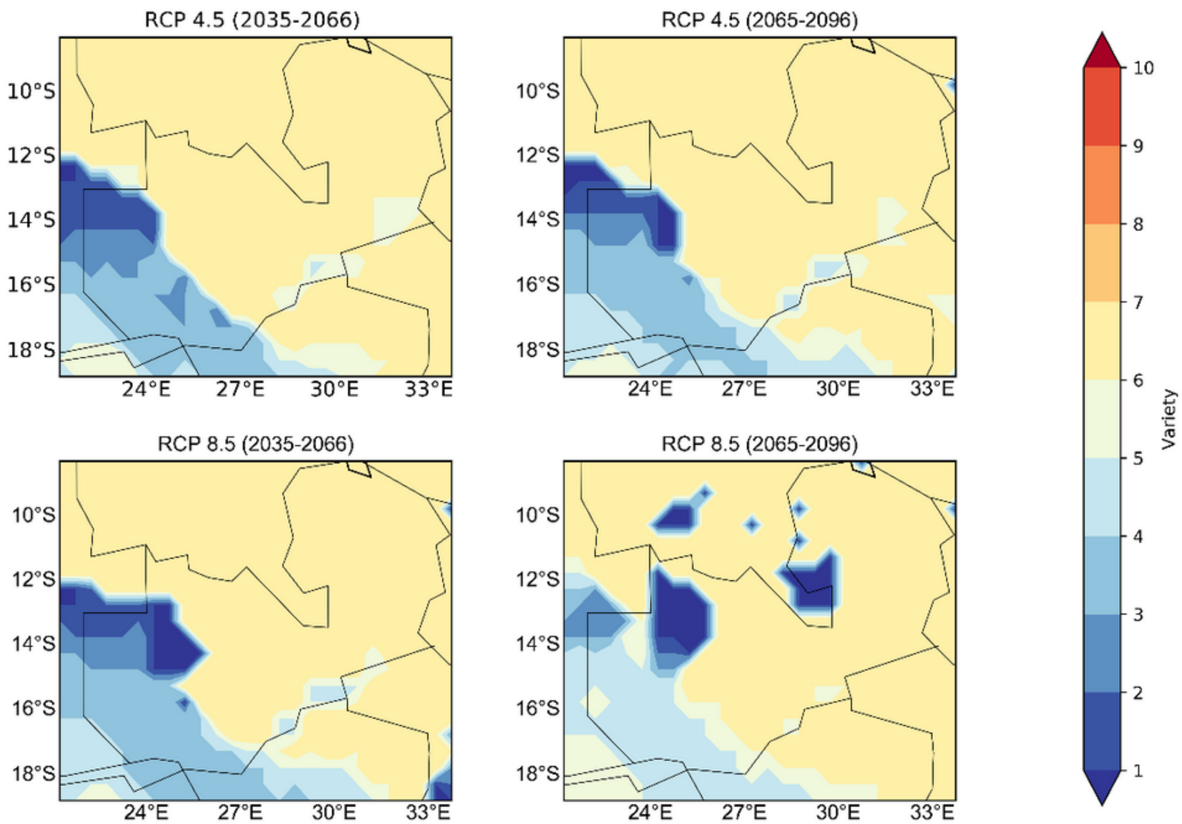

Figure 5

Best suited maize variety (see table 1) in 2035-2066 and 2065-2096 under climate scenarios RCP 4.5 and RCP 8.5.

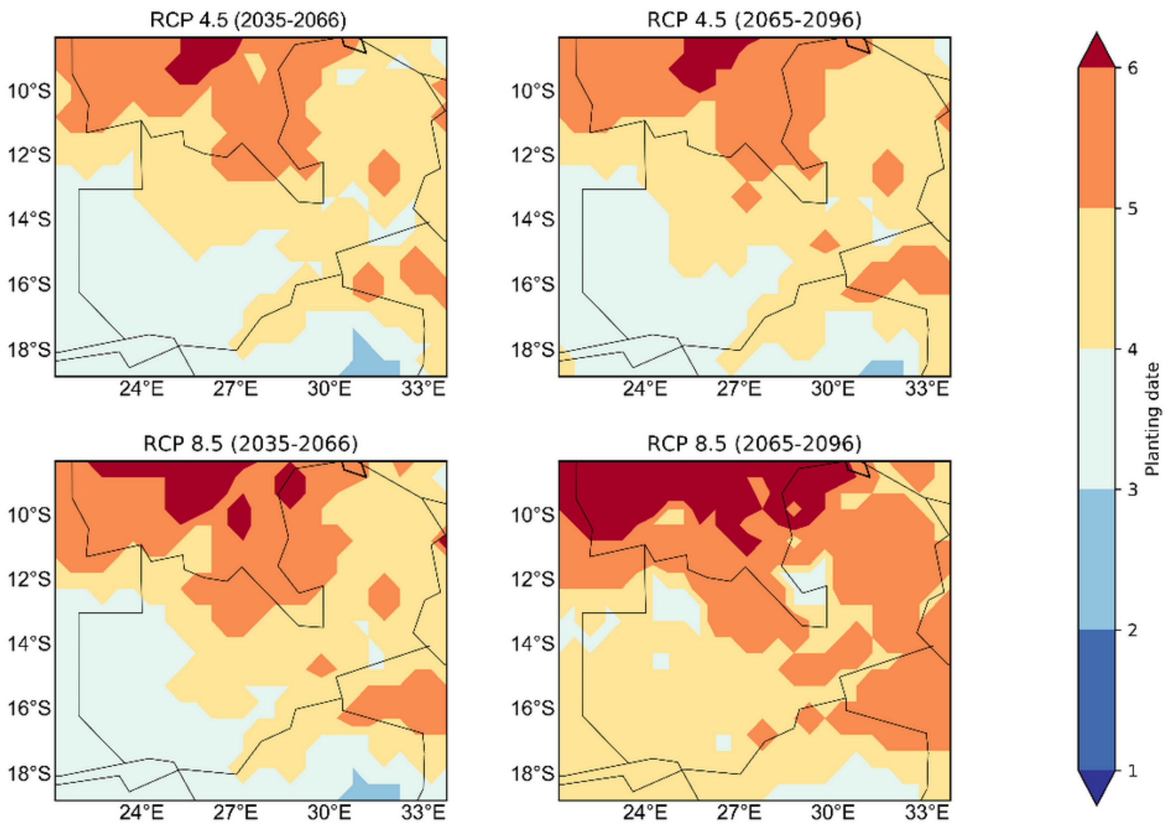

Figure 6

Best suited maize planting date (see table 1) in 2035-2066 and 2065-2096 under climate scenarios RCP 4.5 and RCP 8.5.