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ORIGINAL PAPER

Vulnerability of African maize yield to climate change and variability during 1961–2010

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Abstract Because of the necessity of feeding growing populations, there is a critical need to assess the variation and vulnerability of crop yields to potential climate change. Databases of maize yields and climate variables in the maize growing seasons were used to assess the vulnerability of African maize yields to climate change and variability with different levels of management at country scale between 1961 and 2010. The ratios of time-series trends or standard deviations of detrended yield deviation and climate variables including temperature (T_{mean}), precipitation (P) and standardized precipitation evapotranspiration index (SPEI) were used to analyze the vulnerability of maize yields to climate change and variability for each country in Africa. Most countries, where soil fertility had been declining owing to low levels of fertilizer use over many years and limited water resources, had decreasing maize yields. The negative impacts of increasing temperature and decreasing precipitation and SPEI on maize yields progressively increased at the whole continent scale over the time period studied. During the maize growing seasons 1961–2010, each 1°C of T_{mean} increase resulted in yield losses of over 10% in eight countries and 5-10% in 10 countries, but yields increased by more than 5% in four relatively cool countries. Decreases of 10% average P resulted in more than 5% decreases in yields in 20 countries and each decrease of 0.5 SPEI resulted in over 30% losses of maize yields in 32 countries. Greater T_{mean} or P or SPEI variability in Africa may also bring about greater fluctuations in yield. In addition, countries with better management, which would be expected to have better yields, may be more vulnerable to yield losses due to adverse physical conditions. Better irrigation and fertilizer application will be important to sustain higher yields in the future, as will the development of maize varieties with greater heat and drought tolerance.

Keywords Climate change · Crop yield · Food security · Africa · Maize · Standardized precipitation evapotranspiration index (SPEI)

Introduction

There is a general consensus that the African climate is warming and drying, and that the temperature has risen by 0.2–2.0 °C during 1970–2004 (IPCC 2007). Most African agriculture depends on climate conditions (Challinor et al. 2007; Jones and Thornton 2003; Parry et al. 1999; Parry et al. 2004; Schlenker and Lobell 2010) and is therefore vulnerable to climate change (IPCC 2007; Kurukulasuriya and Ajwad 2007) especially smallholder systems, prevalent in many parts of Africa with little adaptive capacity (Müller et al. 2011). This implies the need to develop new options and innovations that enhance the resilience of agricultural production and reduce vulnerability to climate change and variability in Africa (Cooper et al. 2008). Effective adaptation requires two pieces of information: how trends in crop yield alter in response to climate change and how crop yields fluctuate with climate variability.

Previous studies have quantified the impacts of climate change on African agriculture at the regional or continental levels, mainly using three types of methods: crop process-based models (e.g., Jones and Thornton 2003; Roudier et al. 2011; Walker and Schulze 2008), statistical models (e.g., Kurukulasuriya et al. 2006; Lobell et al. 2008; Schlenker and Lobell 2010) and econometric models (e.g., Seo et al.

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2009). Müller et al. (2011) indicate that there is potential for positive as well as negative impacts of climate change on agriculture production relative to current production levels. These range from −84% to +62% in process-based models, from −57% to +30% in statistical models, and from −100% to +168% in econometric models. There is considerable spatial and temporal variation in impacts of climate change on maize yields, severe losses of >20% being predicted for 3% to 10% of areas for 2030 and 9% to 33% of areas for 2050 (Thornton et al. 2009). Other studies have concluded consistently that climate change has had considerable impacts on crop yields (Challinor et al. 2007; Chuku and Okoye 2009) and that changes in temperature had much stronger impacts on yields than changes in precipitation (Schlenker and Lobell 2010). Although there are well-established concerns about the impacts of climate change on agriculture and the adaptations of agriculture to climate change in Africa (Lobell et al. 2011a; Waha et al. 2013), most experiments, including management measures, have been conducted on a small scale (Wichelns 2003) and can hardly be used to understand the conditions of the whole continent. With respect to the challenges of growing populations and climate change impacts (Müller et al. 2011; Parry et al. 2005; Rosenzweig and Parry 1994), there is a critical need to provide an assessment of vulnerability of maize yields to climate change and variability, so that effective adaptation options can be appropriately targeted.

Maize is the most widely grown crop in Africa, so it was chosen for analysis in this study with regard to vulnerability of yields to climate change and variability for the period 1961–2010. In order to adapt effectively to climate change, we should know how trends in crop yield follow trends in climate change and how crop yields fluctuate with climate variability. In our study, in addition to mean temperature (T_{mean}) and precipitation (P) in the growing season, we also chose the standardized precipitation evapotranspiration index (SPEI) as representative of drought conditions. These three metrics were used to explore the vulnerability of maize yield to climate change and variability with different management practices, including different levels of irrigation and fertilizer use at country scale in Africa for the past 50 years.

Data and methods

Data

Maize yield data

Data for Maize yield (Y) of each country in Africa for the years 1961–2010 were obtained from the Food and Agriculture Organization (FAO) website (http://faostat.fao.org, FAO 2013). There are two countries, which have data only from the early 1980s/1990s, i.e. Djibouti (from 1981) and Eritrea (from 1993). Because we have no information about the crop calendar for the Djibouti, data from this country was not used in our study. The calculation for Eritrea is only from 1993.

Climate data

Average historical temperature (T_{mean}) and precipitation (P) in the maize growing season for the period 1961–2010 were generated from the 0.5° × 0.5° gridded monthly datasets produced by the Climate Research Unit of the University of East Anglia (CRU TS3.20) spanning the period 1901–2011 (Harris et al. 2012). SPEI for the maize growing season in Africa, as a climatic drought index, was taken from SPEIbase v2.2 in this study (Beguería et al. 2010; Vicente-Serrano et al. 2010a; Vicente-Serrano et al. 2010b). The CRU TS3.20 dataset was used as input for the SPEI calculation (http://badc.nerc.ac.uk/browse/badc/cru/data/cru_ts_3.20). Time scales from 1–48 months are covered by the global 0.5° gridded SPEI dataset. According to the calculation method, SPEI is a standardized variable, and an SPEI of 0 indicates a value corresponding to 50% of the cumulative probability of drought.

Climate data for each grid in the periods of the maize growing season was used to calculate the impacts of climate change and variability on maize yields. To obtain the monthly T_{mean}, P and SPEI specific to the location where and time of year when maize is grown, the T_{mean} and P data were averaged temporally over the maize growing season months for each 5′ × 5′ grid from a global crop calendar (Sacks et al. 2010), and the time scale for SPEI calculation was the same as the growing season for each grid. Then, spatially weighted averages of the CRU data and SPEI data of the 5′ × 5′ gridded data of African maize area were computed for each country (Monfreda et al. 2008). This was an important step for accurately analyzing the impacts of climate change and variability on maize yields.

Irrigation and fertilization data

To explore the vulnerability of maize yields to climate change and variability with different management levels, we used gridded datasets for irrigation and global fertilizer application. The gridded irrigation dataset at 5′ × 5′ grid-cells is based, among other information, on the geographical distribution of areas equipped for irrigation around the year 2000 (Siebert et al. 2005). We used a dataset for global rates of fertilizer application which is also representative of the year about 2000 and available at 0.5° resolution in latitude by longitude (Potter et al. 2010).

Methods

To evaluate the relationship between the time series for maize yield and climate, we should minimize the influence of slowly changing factors with time such as crop management. Methods of first-differences time series and detrending the time series produced qualitatively similar results, which were evaluated in the research of Lobell et al. (2007). In this study, we calculated the detrended yield (ΔY) and time series trend of yield (Y_t) based on the method of detrending the time series for yield. Trends for maize yield were calculated by linear regression analysis with years, that is,

$$Y = ax + b \tag{1}$$

where Y is the maize yield; x is the year; a is the linear trend; and b is the intercept. Thus,

$$Y_t = ax \tag{2}$$

and

$$\Delta Y = Y - Y_t \tag{3}$$

In order to analyze the relative yield change due to climate change/variability for each country, the ratios of detrended yield (ΔY) and time series trend of yield (Y_t) were calculated as ΔY_d,

$$\Delta Y_d(\%) = \Delta Y / Y_t \times 100 \tag{4}$$

The correlation coefficients (r) between ΔY_d and T_{mean} or P or $SPEI$ were calculated to analyze the relationships between yields and climate variables. We then performed linear regressions to analyze the time series trends of Y, ΔY_d, T_{mean}, P and $SPEI$ for the period 1961–2010. The standard deviations (SDs) ($\Delta Y_d SD$, $T_{mean}SD$, PSD and $SPEISD$) of the latter four variables (ΔY_d, T_{mean}, P and $SPEI$) for these 50 years were also calculated, which represented fluctuations in yield of maize and variability of the climate during the growing-season during this period. In addition, the SDs of ΔY_d, T_{mean}, P and $SPEI$ were standardized to a range between 0 and 1, so the ratios could be calculated between the SDs of yield data and climate variables and compared with each other.

$$SDstd = \frac{x - \min(x)}{\max(x) - \min(x)} \tag{5}$$

where SD_{std} are the standardized values for SDs of ΔY_d, T_{mean}, P and $SPEI$ data for each country ($\Delta Y_d SD_{std}$, $T_{mean}SD_{std}$, PSD_{std} and $SPEISD_{std}$); x represent the original SDs of ΔY_d, T_{mean}, P and $SPEI$ for each country; min(x) are the minimum values of SDs of ΔY_d, T_{mean}, P and $SPEI$ in all African countries, and max(x) are the maximum values of SDs of ΔY_d, T_{mean}, P and $SPEI$ in these countries.

We used the ratios of time-series trends of detrended yield deviation (ΔY_d) and climate variables (T_{mean}, P and $SPEI$) to analyze the vulnerability of maize yields to climate change for each country in Africa. The ratios represent the relationship between 1 °C, or 10% of average P (P_{ave}), or 0.5 $SPEI$ values and ΔY_d. Similarly, the ratios of $\Delta Y_d SD_{std}$ to $T_{mean}SD_{std}$ or PSD_{std}, or $SPEISD_{std}$ were analyzed for the impacts of climate variability on fluctuation in maize yield, ΔY_d.

Results

The spatial-temporal trends of maize yield

Maize was the crop with the largest area in Africa in 1961–2010, but many African countries had lower maize yields (less than 1,500 kg/ha) during these years (Fig. 1a). Most farmers outside Egypt and South Africa have historically applied little irrigation and fertilizer to their crops (Fig. 2). In contrast, Egypt had better management conditions, including greater irrigation (Fig. 2a) and fertilizer application rates of nitrogen (N) (Fig. 2b) and phosphorus (P) (Fig. 2c) and had the highest average maize yield (5,290 kg/ha) in Africa for the period (Fig. 1a). This was followed by South Africa with 2,211 kg/ha, which had moderate levels of irrigation and fertilizer application. Most countries in Central Africa had yields of less than 1,000 kg/ha (Fig. 1a), where soil fertility had been declining because of low levels of fertilizer application for many years and limited water resources (Fig. 2). Although maize is not normally irrigated, maize that is irrigated, other conditions being equal, has much higher yields (You et al. 2009).

Although fertilizer use and irrigation water were limited (Fig. 2), maize yields of many African countries increased significantly ($p<0.05$) during the period 1961–2010 (Fig. 1b) but some, mostly in the South, West and North showed decreasing trends (Fig. 1c). Algeria and Cote d'Ivoire were the worst with yield decreases of more than 1% per year. The SDs of ΔY_d for maize in Africa showed that countries which had the greatest decrease ΔY_d (Fig. 1c) also had the greatest instability (Fig. 1d).

Spatial-temporal patterns of climate change and variability in the maize growing season

There is an obvious spatial distribution pattern of average T_{mean} for the maize growing season in Africa during the period 1961–2010. Higher average T_{mean} areas are located particularly in a line near 10°N of most countries in West Africa as well as Chad, Sudan and Somalia (Fig. 3a). More than half of the maize areas of Africa had less than 800 mm average P in

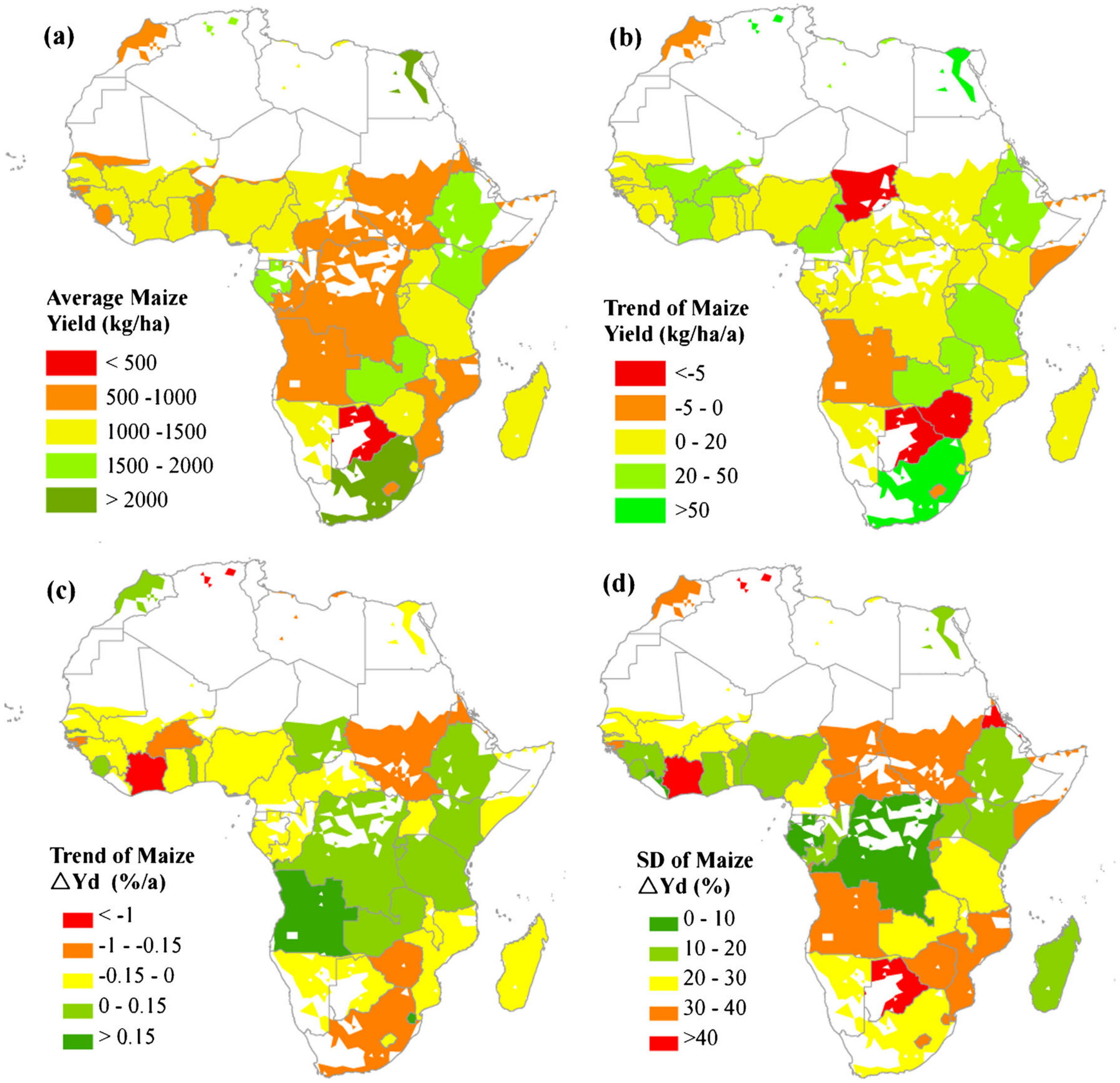


Fig. 1 Trends and variability of maize yields for the period 1961–2010 in Africa, (**a**) average maize yield, (**b**) trends of maize yield, (**c**) trends of detrended yield deviation (ΔY_d) and (**d**) standard deviations (SDs) of detrended yield deviation (ΔY_d)

the whole maize growing-season every year during the period 1961–2010 (Fig. 3b). Average *SPEI* values for the period 1961–2010 in most of the African countries were below 0.1 (Fig. 3c).

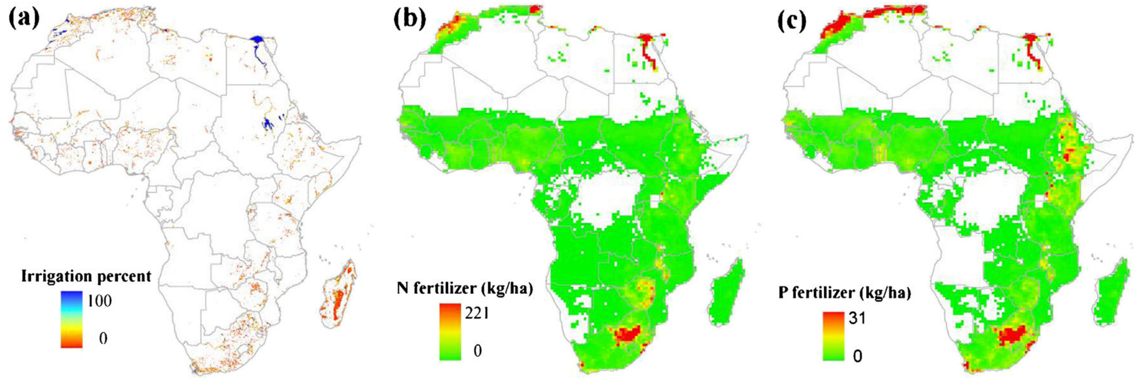


Fig. 2 The spatial patterns of (**a**) irrigation and (**b**) fertilizer application of nitrogen (N) and (**c**) phosphorus (P) in Africa around the year 2000

Time series of T_{mean} and P in the growing season revealed warming and drying trends in most African countries (Fig. 3d and e). Most of the more northerly African countries had larger warming trends in the maize growing season, especially Morocco, Algeria and Sudan with T_{mean} trends of more than 0.3°C/decade (Fig. 3d). Gabon in Central Africa had the smallest T_{mean} increase with 0.05 °C/decade. Because more than 95% of cropland in Africa is rainfed, rainfed agriculture is the dominant source of African crop production (Wichelns 2003). Agricultural systems are reliant on precipitation as nearly the sole source of moisture for crop growth, so P trends (Fig. 3e) and variability (Fig. 3h) were inevitably mirrored in both crop yields (Fig. 1b and c) and variability (Fig. 1d). In the past 50 years, most African countries had decreasing patterns of P in the maize growing seasons (Fig. 3e). Only three countries of Central Africa (Gabon, Republic of Congo and Equatorial Guinea) and Madagascar had increasing trends of P, and the other countries had no significant trends or decreasing trends of P (Fig. 3e). Only Madagascar, Somalia and Ethiopia in East Africa had increasing trends of *SPEI* with more than 0.01 per decade (Fig. 3f).

African countries had similar distributions of T_{mean} SDs in the maize growing seasons to those of T_{mean} trends. Overall, countries with larger T_{mean} trends had larger SDs. This was particularly evident in Equatorial Guinea with larger T_{mean} trends, which also had larger SDs in the maize growing seasons (Fig. 3g). Most countries in Northern and Central Africa had smaller SDs of P, especially Egypt, Libya and Tunisia (Fig. 3h). Smaller range of average *SPEI* (Fig. 3c) in the period 1961–2010 and larger range of *SPEI* SDs (Fig. 3i) showed that the occurrence of droughts varied greatly in different years. Although the average *SPEI* values were more than 0, most of *SPEI* SDs were more than 0.6 (Fig. 3i).

To put the magnitude of trends in context, we further normalized them by the standard deviation (SD) of year-to-year fluctuations according to the method of Lobell et al. (2011b). For example, if the ratio of the total trend of T_{mean} for the 50-year period and T_{mean} SD is 1.0, it means that temperatures in 2010 were 1 SD higher than that in 1961 (Fig. 3j). We found that 95% of countries experienced T_{mean} trends in maize growing regions from 1961 to 2010 exceeded at least one standard deviation of year-to-year variability for this period, and approximately 40% of all African countries experienced trends of more than 2 SD (Fig. 3j). Absolute values of P trends in all African countries were smaller than 1 SD in all African countries (Fig. 3k). Roughly one-third of African countries had decreasing P trends larger than 0.5 SD (Fig. 3k), indicating serious drying trends in the maize growing seasons in these countries, and 35% of African countries experienced decreasing *SPEI* trends for the period 1961–2010 larger than 1 SD, which indicated that serious droughts also occurred during this period (Fig. 3l).

The correlation coefficients between climate factors and maize yields

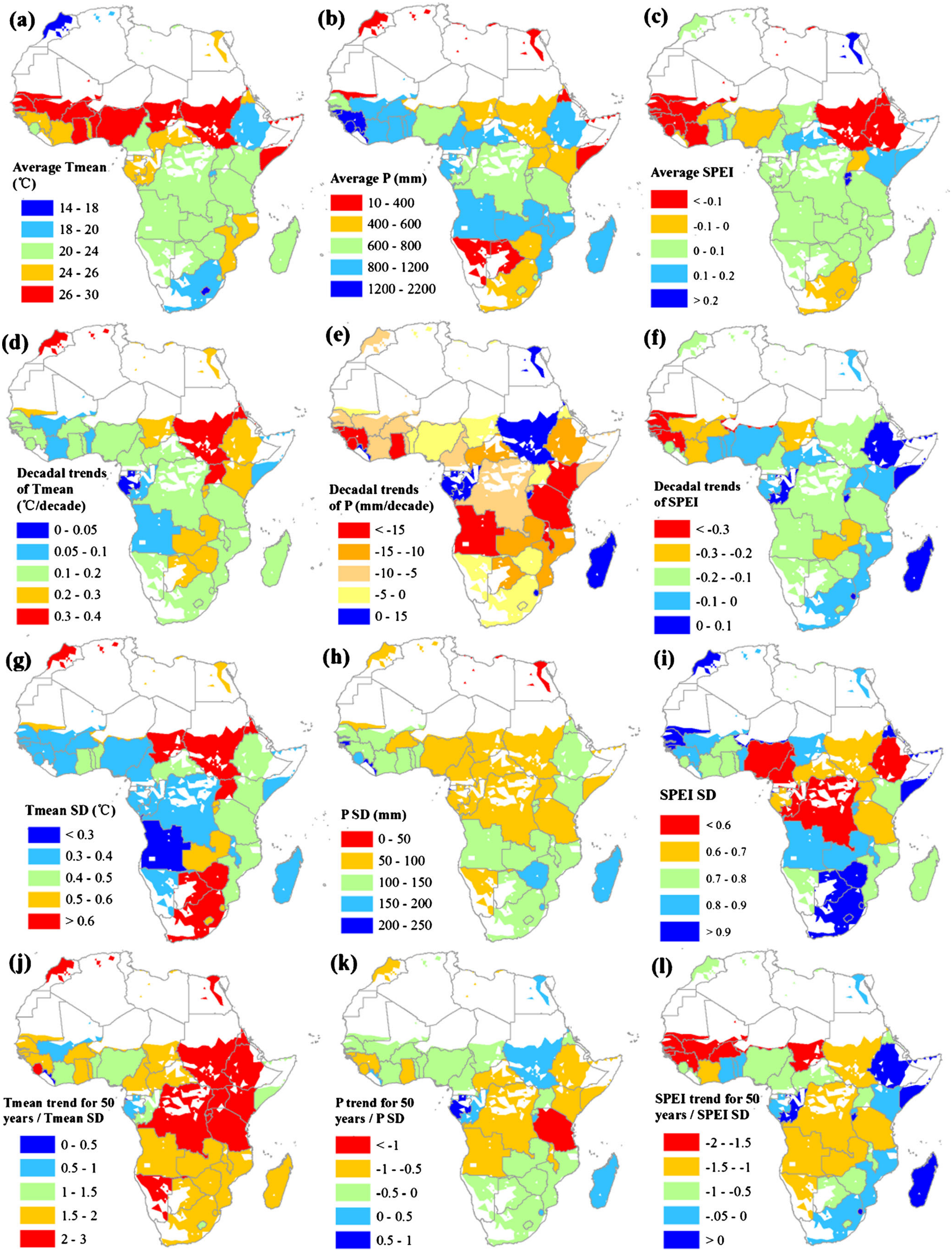
Most African countries have negative correlations between ΔY_d and T_{mean} especially Zimbabwe, Rwanda, Mozambique of East Africa, Gabon of Central Africa, Morocco of North Africa, South Africa and Namibia of Southern Africa, and Benin, Burkina Faso and Togo of West Africa (Fig. 4a). Most African countries have positive correlations between ΔY_d and P especially in Mozambique, Zambia, Malawi, and Zimbabwe of East Africa, Angola and Gabon of Central Africa, Morocco of North Africa, Namibia, Swaziland and South Africa of Southern Africa, and Gambia, Guinea, Senegal, Cote d'Ivoire, Nigeria, Mauritania, Burkina Faso and Niger of West Africa (Fig. 4b). Most African countries have positive correlations between ΔY_d and *SPEI* especially in Madagascar, Cameroon, Algeria, Libya, Benin, Cote d'Ivoire, Gambia and Sierra Leone (Fig. 4c).

The vulnerability of maize yields to climate change and variability in Africa

The vulnerability of maize yields to climate change trends

Figure 5a, b and c provided the spatial impacts of T_{mean}, P and *SPEI* on maize yields in Africa for the period 1961–2010. For the past 50 years, increased temperature trends (Fig. 3d) significantly affected maize yields in most African countries (Fig. 5a). A 1°C T_{mean} increase decreased maize yields of 8 countries by over 10%: South Africa in Southern Africa, Cote d'Ivoire, Mali, Guinea-Bissau and Burkina Faso in West Africa, and Algeria, Libya and Sudan in North Africa. Maize yields decreased by 5–10% due to 1°C T_{mean} increase occurred in 10 countries: Eritrea, Zimbabwe and Malawi in East Africa, Egypt in North Africa, Senegal, Benin and Ghana in West Africa, Central Africa Republic and Cameroon in Central Africa, and Namibia in Southern Africa (Fig. 5a). In addition, maize yields in four relatively cool countries (average T_{mean} less than 24°C, such as Zambia and Tanzania in East Africa, Swaziland in Southern Africa and Angola in Central Africa) may gain from warming with more than 5% increase of maize yields with 1°C increase of T_{mean} (Fig. 5a).

Decreasing P trends in Africa (Fig. 3e) also had large negative impacts on maize yields in most of the countries during the period 1961–2010 (Fig. 5b). Fig. 5b showed that the decrease of 10% P_{ave} resulted in more than 5% decrease of maize yields in 20 countries in Africa (Malawi, Tanzania, Burundi, Eritrea and Mozambique in East Africa, Central African Republic and Cameroon in Central Africa, Algeria, Libya and Sudan in North Africa, South Africa in Southern Africa, Burkina Faso, Gambia, Guinea-Bissau, Nigeria, Togo, Benin, Cote d'Ivoire, Ghana and Senegal in West Africa).


(a)
Average Tmean (℃)
14 - 18
18 - 20
20 - 24
24 - 26
26 - 30
(b)
Average P (mm)
10 - 400
400 - 600
600 - 800
800 - 1200
1200 - 2200
(c)
Average SPEI
< -0.1
-0.1 - 0
0 - 0.1
0.1 - 0.2
> 0.2
(d)
Decadal trends of Tmean (℃/decade)
0 - 0.05
0.05 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.4
(e)
Decadal trends of P (mm/decade)
< -15
-15 - -10
-10 - -5
-5 - 0
0 - 15
(f)
Decadal trends of SPEI
< -0.3
-0.3 - -0.2
-0.2 - -0.1
-0.1 - 0
0 - 0.1
(g)
Tmean SD (℃)
< 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.6
> 0.6
(h)
P SD (mm)
0 - 50
50 - 100
100 - 150
150 - 200
200 - 250
(i)
SPEI SD
< 0.6
0.6 - 0.7
0.7 - 0.8
0.8 - 0.9
> 0.9
(j)
Tmean trend for 50 years / Tmean SD
0 - 0.5
0.5 - 1
1 - 1.5
1.5 - 2
2 - 3
(k)
P trend for 50 years / P SD
< -1
-1 - -0.5
-0.5 - 0
0 - 0.5
0.5 - 1
(l)
SPEI trend for 50 years / SPEI SD
-2 - -1.5
-1.5 - -1
-1 - -0.5
-.05 - 0
> 0

◀ **Fig. 3** Trends and variability of climate variables in the maize growing season for the period 1961–2010. (**a**) average T_{mean}, (**b**) average P, (**c**) average $SPEI$, (**d**) decadal trends of T_{mean}, (**e**) decadal trends of P, (**f**) decadal trends of $SPEI$, (**g**) SDs of T_{mean}, (**h**) SDs of P, (**i**) SDs of $SPEI$, (**j**) the ratio of total trends of T_{mean} for 50 years and T_{mean} SDs, (**k**) the ratio of total trends of P for 50 years and P SDs and (**l**) the ratio of total trends of $SPEI$ for 50 years and $SPEI$ SDs

Drought in the maize growing season in Africa had increasing trends (Fig. 3f), which affected maize yield trends to a large extent (Fig. 5c). When $SPEI$ values decreased by 0.5, 32 countries suffered over 30% losses of maize yields, i.e. Guinea, Gambia, Guinea-Bissau, Mauritania, Niger, Nigeria, Togo, Benin, Ghana and Sierra Leone in West Africa, Botswana, Lesotho, South Africa and Namibia in Southern Africa, Algeria, Libya, Egypt, Morocco and Libya in North Africa, Equatorial Guinea, Central African Republic and Cameroon in Central Africa and Madagascar, Malawi, Tanzania, Zimbabwe, Burundi, Kenya, Mozambique, Somalia, Uganda and Tanzania in East Africa. However, maize yields in most of the countries near the equator were less affected by droughts (countries with red colors in Fig. 5c).

The vulnerability of maize yields to climate variability

Yield instability is another index with which to analyze the vulnerability of agriculture to climate change. The ratios of $\Delta Y_d SD_{std}$ and $T_{mean} SD_{std}$ or PSD_{std}, or $SPEISD_{std}$ were used to show the yield fluctuation distributions for each country due to T_{mean} or P, or $SPEI$ variability, respectively. Figure 5d shows that some countries including Sudan and Morocco in North Africa, Uganda in East Africa and Botswana in Southern Africa had high instability, which had large impacts of T_{mean} trends on yield trends. This meant that a small variance of T_{mean} can result in a large variance of maize yields in these countries. Figure 5e also shows that some countries in Western and Southern countries with greater impacts of decreasing P had greater instability of maize yields. Gabon in Central Africa, Madagascar in East Africa, South Africa in Southern Africa and most of the countries in West Africa (including Ghana, Togo, Benin, Senegal, Mali and Guinea) had unstable maize yields which correlated with variability of P. $SPEI$ variability led to greater instability of maize yields in the Republic of the Congo, Cameroon and Equatorial Guinea in Central Africa, Burkina Faso in West Africa, Namibia in Southern Africa, and Uganda in East Africa (Fig. 5f).

Discussion

The vulnerability characters with different management conditions

African countries which had higher trends in maize yields or better management conditions also had higher yield fluctuations during 1961–2010. For example, yield losses were progressively larger due to 1°C warming in the countries with higher trends in maize yields (Fig. 6a), which suggests that countries with better management conditions may also be more vulnerable to losses. In order to further analyze this phenomenon, we classified irrigation (and fertilizer application) into two classes and compared the changes of ΔY_d due to 1°C warming and 10% average decrease in P under (1) high levels of irrigation (with N and P fertilizer application) and (2) low levels of irrigation or none (also with N and P fertilizer application) (Fig. 6b, c and d). We found that countries with higher irrigation, N and P fertilizer application had greater responses to increasing temperature. This result was consistent with previous results studied by statistical models in Africa that were based on FAO statistical data (Schlenker and Lobell 2010), which indicated that fertilizer stress tended to mute the response to heat stress. Schlenker and Lobell (2010) also showed that Zimbabwe and South Africa with the highest fertilizer use in Sub-Saharan Africa were

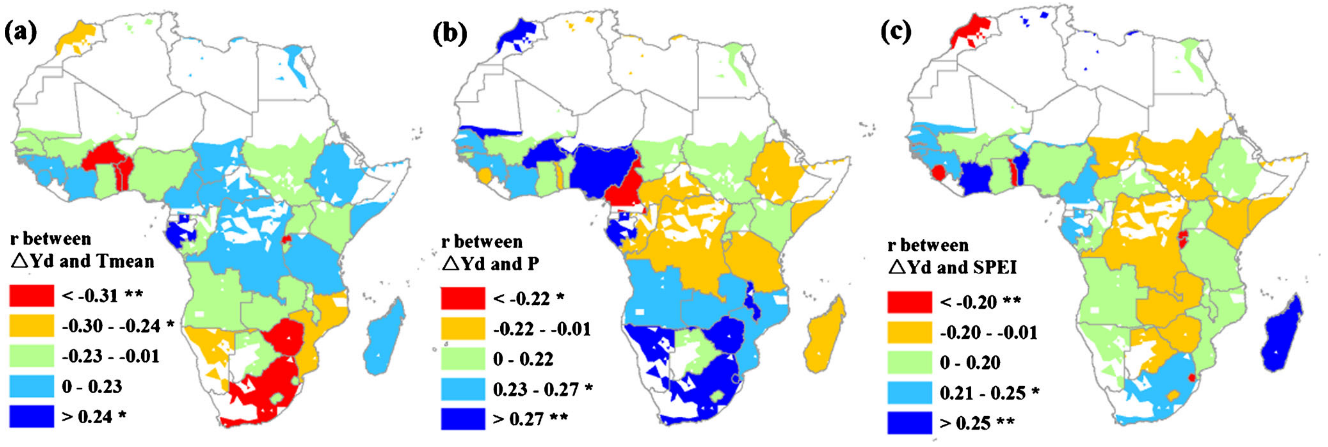


Fig. 4 Correlation coefficients (r) between (**a**) $\triangle Y_d$ and T_{mean}, (**b**) $\triangle Y_d$ and P and (**c**) $\triangle Y_d$ and SPEI

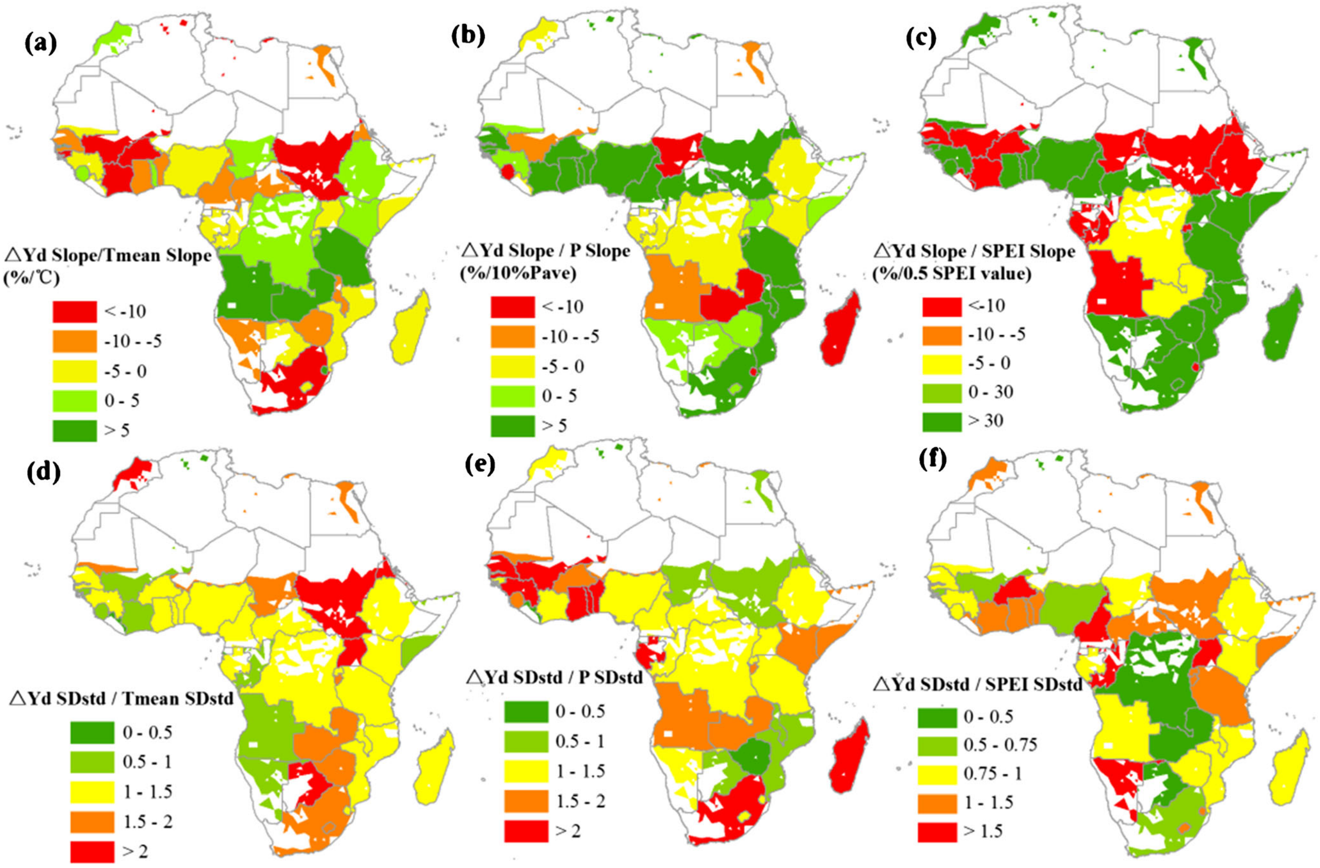


Fig. 5 The impacts of trends and variability of climate changes on maize yields. (**a**) ΔY_d slope/ T_{mean} slope, (**b**) ΔY_d slope/ P slope, (**c**) ΔY_d slope/ $SPEI$ slope, (**d**) $\Delta Y_d SD_{std}$/ $T_{mean}SD_{std}$, (**e**) $\Delta Y_d SD_{std}$/ PSD_{std} and (**f**) $\Delta Y_d SD_{std}$/ $SPEISD_{std}$

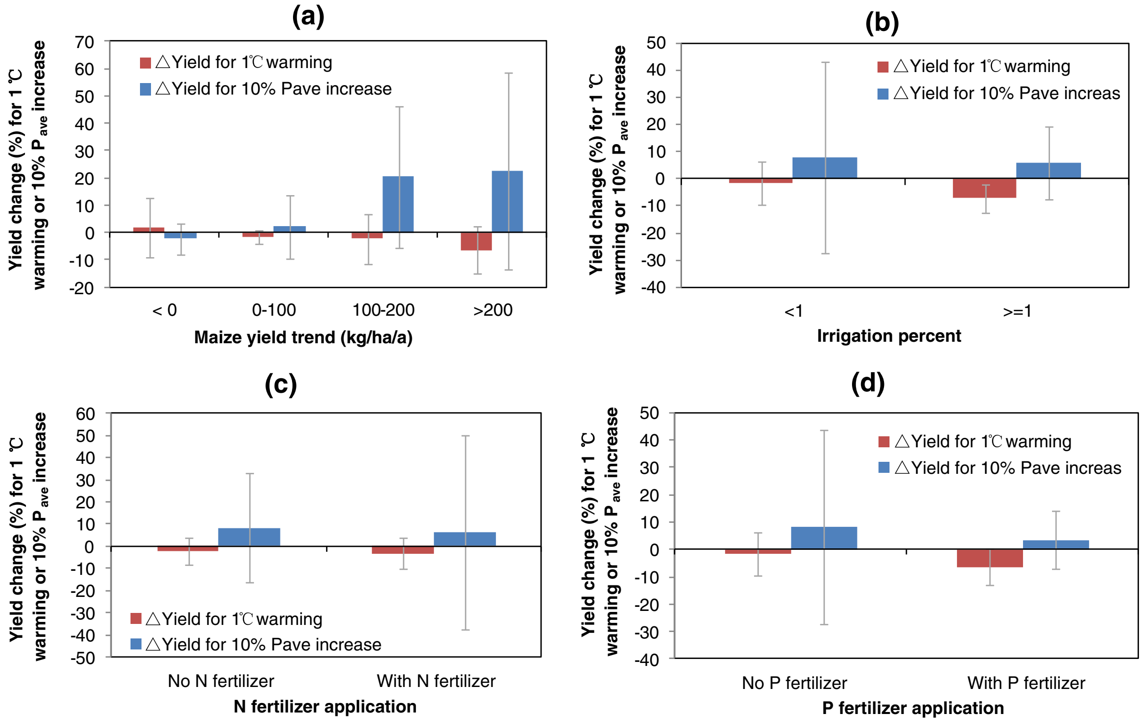


Fig. 6 Maize yield change (%) for 1 °C warming or P_{ave} increased by 10% under different management conditions, (**a**) maize yield trends, (**b**) irrigation percent, (**c**) N fertilizer application and (d) P fertilizer application

more susceptible to temperature increases; on the contrary, the remaining countries had smaller average yields but also showed lower sensitivities to higher temperatures. This finding does not necessarily argue against increased fertilizer use, but rather emphasizes high-yielding varieties are grown in these countries which are more susceptible to heat stress (Schlenker and Lobell 2010). Moreover, in this statistical analysis two different equations were used for with-fertilizer use and no-fertilizer use with only 16 (with N fertilizer) or 5 (with P fertilizer) countries in the first group, which leads to large standard errors, and probably difficulties in comparing them.

Uncertainties and limitations

Although climate change influenced maize yields at a broad scale, country-level assessments can miss some critical details (Thornton et al. 2009). Our study relied mainly on statistical analyses based on reported harvest data and gridded climate data at month scale with considerable uncertainties. Firstly, successful adaptation strategies are critical for food security, and crop yields with different adaptation measures in one country having different responses to climate change and variability in another (Thornton et al. 2011). For example, the farmers' choice of adequate crops, cropping systems and sowing dates can be an important adaptation strategy to combat climate change (Waha et al. 2013). For maize in Africa, changing varieties may be an appropriate adaptive strategy in response to changing heat and moisture conditions (Conway and Toenniessen 1999; Lobell et al. 2011a). Schlenker and Lobell (2010) suggested that well-fertilized modern seed varieties were more susceptible to heat related losses but drought may cause larger yield losses (Schlenker and Lobell 2010). Furthermore, climate impacts on agriculture are highly uncertain because of the complex process of direct and indirect effects of weather on crop yields (Müller 2011). Early maturing, medium maturing and late maturing cultivars have different yields, and their variability in relation to the impact of climate change/variability may also be different. Using spatially weighted averages of climate data at country-level ignores differences between regions and farmers within country (Schlenker et al., 2010). Because crop yield datasets in Africa for finer scales scarcely exist, these within-country heterogeneities have not been considered. Moreover, although the standard deviations of climate variables were considered in this study, the impacts of extreme climate conditions including droughts, floods and high temperature episodes, which may become more frequent in parts of Africa, were not quantified. Lobell et al. (2011a) showed a nonlinear relationship between warming and yields, that is, each degree day spent above 30 °C reduced the final yield by 1% to 1.7% according to different moisture conditions. Finally, we noted that average yields in drier areas were over-estimated when crop failure was widespread in poor years because the FAO statistical data for crop yields were derived from 'harvested area' (Cooper et al. 2008).

Summary and conclusions

This study identified spatial patterns of vulnerability of maize yield to climate change and climate variability at the country scale in Africa for the period of 1961–2010 and explored the vulnerability characters at different levels of irrigation and fertilizer use. The results suggested that the already occurring negative impacts of increasing temperature and droughts on maize yields were progressively increasing at the whole continent scale. In Africa, each 1 °C of T_{mean} increase in the maize growing season resulted in yield losses in 8 countries by over 10%, 10 countries by 5-10%, but also resulted in maize yield increases by more than 5% in 4 relatively cool countries. Each 10% average decrease in P during 1961–2010 in the maize growing season resulted in more than 5% losses of maize yields in 20 countries. Each 0.5 SPEI decrease in the maize growing season resulted in over 30% losses of maize yields in 32 countries. Greater T_{mean} or P or $SPEI$ variability in Africa may also cause larger yield fluctuation.

Appropriate adaptation strategies to climate change and climate variability therefore include planting of drought tolerant cultivars and greater investment in irrigation and fertilizer application (Akerele et al. 2013; Cairns et al. 2013; Marenya et al. 2012; Thornton et al. 2010). Better irrigation and fertilizer application are important for sustaining higher yields in the future, but fluctuations in yield may be larger than maize grown under inferior management practices. Future work with yield data both on a finer scale and for different management procedures will help to optimize the reduction of the negative impacts of climate change and variability.

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