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IMPACTS OF CLIMATE CHANGE ON PLANT GROWTH: IMPLICATIONS FOR POLICY AND RESEARCH

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ABSTRACT: *Plant growth is heavily facilitated by the extent to which many interacting climate variables remain within appropriate conditions. The Ongoing global climatic change can significantly alter conditions for plant growth, in turn upsetting ecological and social systems. While there have been substantial developments in understanding the physical features of climate change, complete studies incorporating climate, biological, and social sciences are less common. This paper used climate projections under alternative mitigation situations to show how changes in environmental variables that limit plant growth could influence ecosystems, research, policies and humans. Results showed multiple climate variables becoming limiting for plant growth, particularly in tropical areas, which resulted in considerable reductions in plant yields. Furthermore, the paper posited that reductions in plant growth due to unsuitable growing days can lead to less suitable condition for plant growth and tree mortality can trigger ecological responses, including changes in plant community composition. The paper concludes by recommending that afforestation programs should be vigorously pursued.*

KEYWORD: Climate, Ecology, Plant Growth, Radiation, Temperature, Water.

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INTRODUCTION

Growth is defined as "an irreversible permanent increase in size of an organ or its part or even of an individual cell." (Borlang 2007). In other words, Growth is the most essential and obvious characteristics of living beings and is accompanied by several metabolic methods that occurs at the expense of energy. These metabolic methods may be catabolic or anabolic. In case of plants, seed germinates, develops into seedling and later it takes the shape of an adult plant at different stages of growth. Plants exhibits indefinite growth.

Plant growth is a central biological process that is strongly controlled by climate variables (Adger,et.al 2020). Plant productivity influences the operation of ecosystems according to Zachos, et. al. (2018), it fuels the global food web, and is the foundation for some of the most diverse habitats in the world (Hermes et al 2015). Vegetation also sustains humanity Fedoroff et al. (2010) by directly providing oxygen, food, fibre, and fuel. However, plant growth is powerfully limited by climate variables such as air temperature, solar radiation and water availability according to Burke et al., (2009), which are constantly changing in response to ongoing global climate change. These variations are normally connected with a bigger human demand on the planet's resources, which could further stress natural ecosystems and subsequently lead to deficiencies in important goods and services (Hermes et al 2015). While there have been substantial developments in understanding the amount to which individual and multiple climate variables limit plant growth (Fischer, et al. 2010), comprehensive analyses integrating climate, biological, and social sciences are less common.

Additionally, over the next 50 years plants mostly agricultural plants must provide for an additional 3.5 billion people (Borlaug 2007). Production of the three major cereal crops alone (maize, wheat and rice) will need to increase by 70 % by 2050 in order to feed the world's growing rural and urban populations. However, climate change scenarios show that plant production will largely be negatively affected and will impede the ability of many regions to achieve the necessary gains for future food security (Lobel et al.2010). The impact of climate change on plants is all over the world, it will be greatest in the tropics and subtropics, with sub-Saharan Africa (SSA) particularly vulnerable due to the range of projected impacts, multiple stresses and low adaptive capacity (IPCC 2010). Climate change scenarios for SSA include an increase in seasonal and extreme temperature events and intensity of droughts (IPCC 2007), and are likely to result in changes in production and the suitability of current crops. Africa is warming faster than the global average (Collier et al. 2008) and by the end of this century, growing season temperatures are predicted to exceed the most extreme seasonal temperatures recorded in the past century (Borlaug, N. 2007).). There remains greater uncertainty in projected changes in rainfall distribution patterns, with the outputs of climate models for future precipitation often not agreeing on the direction of change for SSA (IPCC 2011).While there is an urgent need to address policies and management strategies at both the country and international levels for plant adaptation to climate change, additional measures are also required to reduce the adverse effects of climate change on plants generally.

Climate change scenarios for SSA include an increase in seasonal and extreme temperature events and intensity of droughts (IPCC 2007), and are likely to result in changes in production and the suitability of current crops. There remains greater uncertainty in projected changes in rainfall distribution patterns, with the outputs of climate models for future precipitation often not agreeing on the direction of change for SSA (IPCC 2010). There appears to be a general trend of increased precipitation in East Africa, with decreased precipitation in Southern Africa

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(IPCC 2007). For West Africa projected changes in rainfall vary greatly making it difficult to infer future climate scenarios (IPCC 2007; Collier et al. 2008)).

This paper will attempt to provide a global-scale perspective, using climate model projections and available socioeconomic and ecological data, to assess how projected climate change will affect the suitability of the planet for plant growth and evaluate potential implications of these changes for Humans, Ecosystems, Research and Policies.

METHODS

Quantifying Plant Growth Climatic Thresholds

Our analysis uses the modern sharing of where plants grow and assumes that climatic conditions at those locations are suitable. Although this is a correlative approach, it provides important relative understandings into how plant growth could be affected by alternative future climates. The rate at which terrestrial vegetative matter is produced (Net Primary Productivity, NPP)) as a proxy for plant growth was used. Derived values of NPP were obtained from 8-d averaged MODIS data (the finest temporal resolution available; data source. MODIS NPP data are modelled using remotely sensed satellite data and have been cross-validated by other studies (Collier et al. 2008). To estimate climate thresholds for plant growth, we overlaid 8-d maps of derived NPP onto 8-d maps of observed temperature (i.e., near-surface air temperature), water availability (using soil moisture in upper 10 cm of the soil column as proxy), and solar radiation (i.e., surface down welling shortwave radiation). This allowed us to calculate the total amount of 8-d NPP produced along gradients of each of the three climate variables and their interactions. We defined NPP climatic thresholds as the boundaries that surround the climatic conditions under which 95% of the world's NPP occurs for each variable and their interactions, for each year between 2008 and 2022. For our analysis, we used the boundaries encompassing all of the yearly boundaries (Fig 1) and define suitable growing days as those days in which projected climatic conditions fall within that multiyear boundary. While some plants grow under extreme conditions, relatively little NPP occurs in these primary cold and arid places (as noted by the steep declines of NPP along climatic variables in Fig 1); using more than 95% of global NPP to include these extremist plants will considerably broaden the climate thresholds and overestimate global suitability for the majority of plant growth.

Calculating Suitable Plant Growing Days

This paper reviews projected global climate change scenarios for SSA and other nations and presents the possible future temperature, climates and monthly precipitation for maize mega environments in SSA and other plants. To estimate for agricultural plant crops in the Sub Sahara Africa SSA, maps, table for temperature and precipitation variation were used to determine how climate can affect cereals crops like maize in the SSA. To estimate the number of suitable days for plant growth each year, we counted the total or successive number of days in a year in which climatic conditions (i.e., temperature, solar radiation soil moisture, and the interactions of these three variables) fall within the global thresholds for plant growth. We obtained daily projections of temperature, soil moisture, and solar radiation from recent Earth System Models developed as part of the Coupled Model Intercomparison Project Phase 5 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

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Daily projections run from 1960 to 2015 simulating anthropogenic and natural climate forcing (i.e., "historical" experiment) and from 2006 to 2100 under three alternative representative concentration pathways: RCP 2.6, RCP 4.5, and RCP 8.5. CO_2 concentrations will reach ~400, ~530, and ~930 ppm by 2100, under RCP 2.6, RCP 4.5, and RCP 8.5, respectively. As of November 2018, there were 14 Earth System Models from 12 centres in eight countries that modelled temperature, soil moisture, and solar radiation at a daily resolution for at least one of the three RCPs (Note: all Earth System Models that we used include feed-backs of plant production on water balance). In total, for all variables and projections, we processed ~1.8 million daily global maps. We quantified the number of suitable plant growing days independently for each model and averaged the results to appraise the multimodel average. Changes in the number of suitable plant growing days (Fig 2) were calculated by subtracting contemporary (2000 to 2009) from future averages (2019 to 2100); decadal averages were chosen to minimize aliasing by inter annual variability.

Analysing Human and Biotic Vulnerability

"Biotic Vulnerability" was analysed in the traditional sense of determining human "exposure" to environmental change, "dependency" in terms of food, jobs, and revenue at stake, and "adaptability" in terms of wealth, assuming that richer countries will have more capacity to respond (Cairns,,et. al., 2012). "Exposure" was quantified as changes in climate suitability for plant growth categorized for each country as follows: "high loss" for countries experiencing reductions in suitable plant growing days in excess of 30%, "medium loss" for countries experiencing losses of 30% to 10%, "no change" for countries that gain or lose up to 10%, "medium gain" for countries gaining 10% to 30%, and "high gain" for countries gaining in excess of 30% more days. "Dependency" was quantified by adding three proportional metrics for each country: percentage of gross domestic product funded by agricultural revenue, percentage of the workforce in the agricultural division, and percentage of NPP appropriated by people (from food, wood, meat, fibre, paper and animal by-products (Fischer, et al., 2010).

Countries were categorized as having "low," "medium," or "high" dependency if their cumulative percentages in those three goods and services ranged from 0% to 33%, >33% to 66%, or >66%, respectively. Finally, "adaptability" was quantified as per capita gross domestic product, under the assumption that richer countries will have greater access to a wider range of adaptive strategies. For the purpose of classification, we used the World Bank categorization of low-, medium-, and high-income countries depending on whether annual per capita gross domestic product was less than US$4,000, between US$4,000 and US$12,000, or greater than US$12,000, respectively.

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RESULTS AND DISCUSSION

In large parts of SSA maize is the principal staple crop, covering a total of nearly 27 M ha (Table 1). Maize accounts for 30 % of the total area under cereal production in this region: 19 % in West Africa, 61 % in Central Africa, 29 % in Eastern Africa and 65 % in Southern Africa (FAO 2010). In Southern Africa maize is particularly important, accounting for over 30 % of the total calories and protein consumed (FAO 2010). Despite the importance of maize in SSA, yields remain low. While maize yields in the top five maize producing countries in the world (USA, China, Brazil, Mexico and Indonesia) have increased three-fold since 1961 (from 1.84 t ha^{-1} to 6.10 t ha^{-1}), maize yields in SSA have stagnated at less than 2 t ha^{-1}, and less than 1.5 t ha^{-1} in Western and Southern Africa. In SSA maize is predominantly grown in small-holder farming systems under rained condition with limited inputs. Low yields in this region are largely associated with drought stress, low soil fertility, weeds, pests, diseases, low input availability, low input use and inappropriate seeds. Reliance on rainfall increases the vulnerability of maize systems to climate variability and change. While farmers have a long record of adapting to the impacts of climate variability, current and future climate change represents a greater challenge because the probable impacts are out of the range of farmers' previous experiences. Climate change will, therefore, severely test farmers' resourcefulness and adaptation capacity (Fischer et. al. 2010).

Table 1 Production of major food crops and the importance of maize in sub-Saharan Africa (data from FAO 2010**)**

	Western Africa	Central Africa	Eastern Africa	Southern Africa[a]	Sub-Saharan Africa
Production area (M ha)					
Cereals (total)	44.39	3.84	28.35	12.12	88.70
Maize	8.34	2.36	8.33	7.93	26.97
Sorghum	11.32	0.75	9.43	3.10	24.60
Cassava	5.10	2.51	1.57	2.79	11.97
Rice	5.23	0.58	0.96	2.10	8.87
Wheat	0.06	0	2.23	0.07	2.36
Maize yields (t ha^{-1})	1.41	1.70	2.49	1.29	1.71
Maize consumption (kg/cap/year)	27.90	17.86	30.33	79.60	39.07
% calories and protein	9.43	7.70	13.44	31.13	15.17

Source: IPCC Fifth Assessment, 2007

Using greenhouse gas emission scenarios prepared for the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report, Lobell, & Burke (2010).) forecast future warming across the Africa subcontinent at 0.2°C per decade (Special Report on Emissions Scenarios (SRES) B1 - low emissions scenario) to over 0.5°C per decade (SRES A2 – high emissions scenario). The greatest warming is predicted over Central and Southern Africa and the semi-arid tropical margins of the Sahara. Dixon et al. (2019) also showed higher levels of warming, at up to 7°C, in Southern Africa in September to November (SRES A1F1 emissions scenario).

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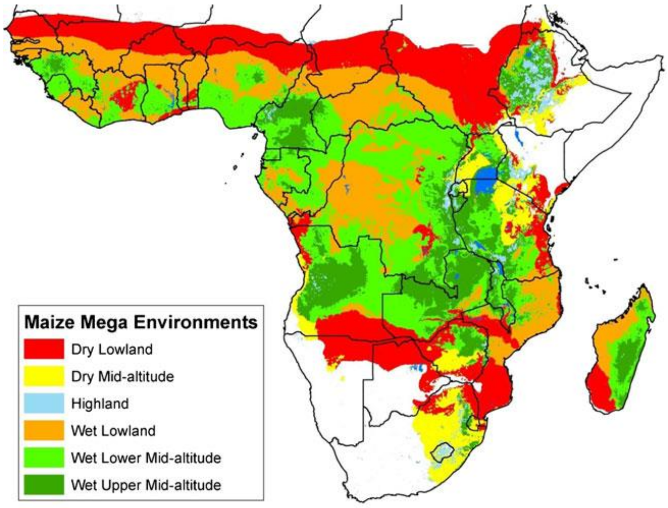
For temperature predictions countries were divided into maize production environments (also called maize mega-environments) Chang, (2020).) based on rainfall and temperature data (Fig. 1 below).

Fig. 1 Maize environments within sub-Saharan Africa (adapted from Hodson et al. 2012)



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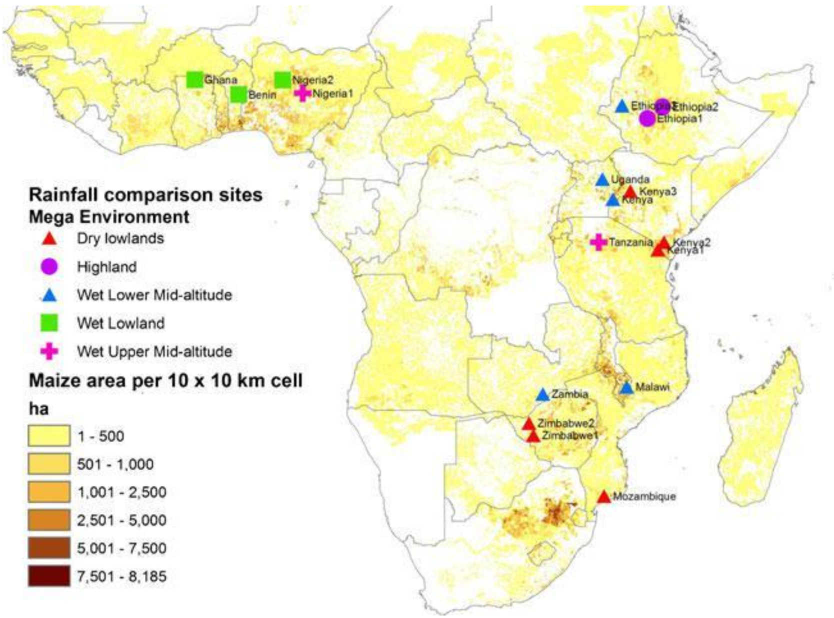
For rainfall predictions 16 areas across all mega-environments were selected. Areas chosen were important regions for maize production as shown in figure 2 below

Fig. 2 Location of sites chosen for rainfall projections



Climate data were downscaled to a 2.5 min (ca 5 km) resolution using an empirical statistical approach. For this, linear or other relationships were established between historically observed climate data at local scales, such as meteorological station measurements and climate model outputs (Shiferaw, 2011).

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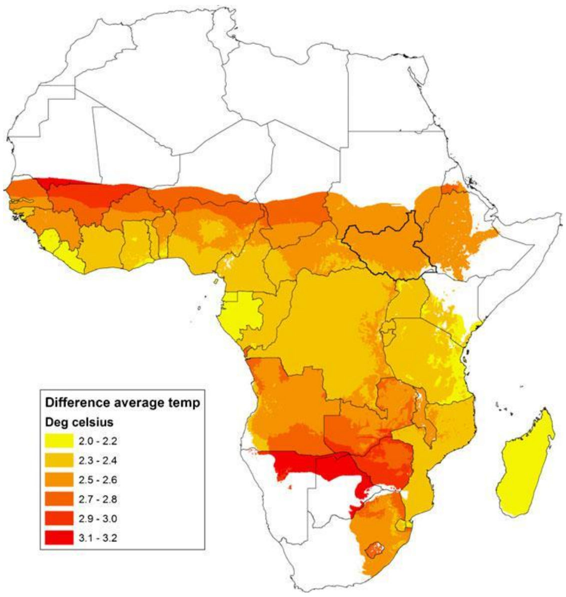
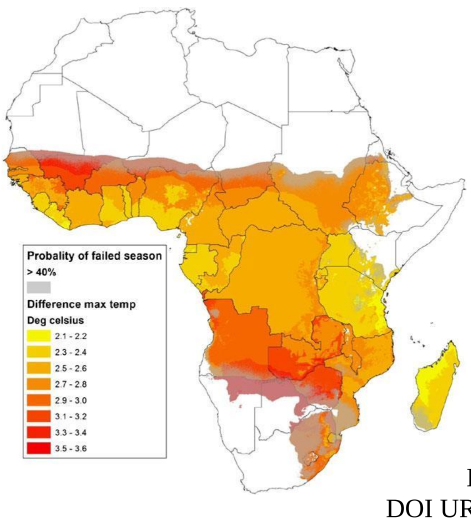
Average temperatures are predicted to increase by 2.4°C within the wet lowlands and wet low and upper mid-altitude environments, and by 2.6°C, 2.5°C and 2.4°C in the dry lowlands, dry mid-altitude and highland environments, respectively as shown in Figure 3 below.

Fig. 3 Increase in average temperatures in maize mega-environments between 1960–2050 using the outputs of 19 GCM's and A2 emissions scenarios



Both maximum and minimum temperatures are predicted to increase, with a greater increase in maximum temperatures. Maximum temperatures are predicted to increase by 2.5°C in wet-upper mid-altitudes, 2.6°C in wet lowlands and wet lowland mid-altitude, 2.7°C in dry lowlands and 2.8°C in dry mid-altitude environments as shown in Figure. 4 below, while minimum temperatures are predicted to increase by 2.0°C in the wet lower and upper mid-altitude, wet lowland and dry mid-altitude, and dry lowland environments.

Fig. 4 Increase in maximum temperature in maize mega-environments between 2050 and 1960–2000 using the outputs of GCM's and A2 emissions scenarios. Regions with a 40 % probability of a failed season due to drought stress are shaded in grey (adapted from Jones 2018)



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In the highlands of Ethiopia rainfall will decrease during the maize growing season (May–October), particularly during the critical reproductive stage. In Nigeria and other West Africa countries, rainfall will decrease during the maize growing season in the wet upper mid-altitude of Nigeria and the wet lowland of Benin. In East Africa, there is a consistent increase in rainfall between December and February across mega-environment.

Modelling maize plants yields using climate projections for temperature and precipitation in ESA revealed that a 2°C increase in temperature will result in a greater reduction in maize yields than a 20 % decrease in precipitation (Lobell and Burke 2010). In Southern Africa, yield losses of maize under drought stress doubled when temperatures were above 30°C. In rained environments, elevated temperatures will increase the evapotranspirative demand from the atmosphere, negatively affecting crop water balance and thus inducing drought stress. In water-limited conditions plants partially close their stomata to reduce water loss through transpiration, resulting in the leaves becoming warmer (Shiferaw, et al 2011) However, elevated CO_2 concentration will decrease evapotranspiration (and increase water use efficiency) through the partial closure of stomata (Zachos, et. al.2018

To further consider the future limiting roles of temperature, solar radiation and water availability, on plant growth generally, we calculated changes in the number of days in a given year that are within suitable climate conditions for plant growth (i.e., suitable plant growing days) under different climate projections. Climate ranges for plant growth is as shown in figure 5 below.

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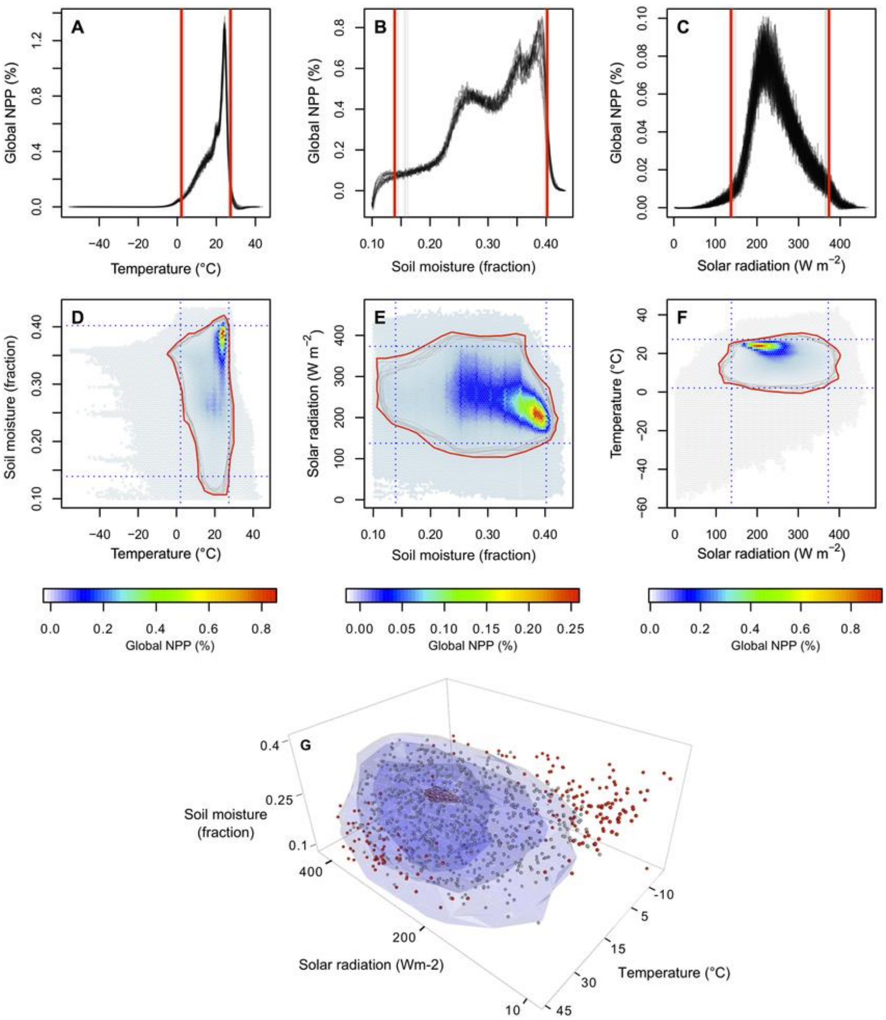

Source:NCEP, 2022

Fig 5. Climatic ranges for plant growth. Global vegetative matter produced (i.e., MODIS NPP, http://neo.sci.gsfc.nasa.gov/view.php?datasetId= MOD17A2_E_PSN) along gradients of temperature (A), soil moisture (B), solar radiation (C), and the interactions of these three variables (D–G). Climate data were obtained from National Centers for Environmental Prediction (NCEP) Reanalysis Daily Averages Grey lines in plots A–F indicate the climatic conditions that surround 95% of the global NPP each year between 2020 and 2021. Red lines encompass all of the yearly boundaries and define the climatic thresholds used in our assessment. A suitable plant growing day was defined as any day falling within these climatic thresholds. Points in plot G are a random subset (i.e., 1,000 points) of global climate conditions and resulting NPP (grey points indicate positive NPP/growth, and red points indicate negative NPP/ respiration). As illustrated, climatic conditions occurring beyond the estimated global thresholds have commonly resulted in plant respiration.

By 2100, the decreasing number of suitable growing days in the tropics will offset optimistic projections at mid- and high latitudes, resulting in minimal changes in the global average number of suitable days under RCP 2.6 and RCP 4.5 but a ~26% reduction in the number of suitable growing days under RCP 8.5 (solid blue lines in Fig 7). For soil moisture and solar radiation, regional differences in the number of suitable plant growing days averaged out

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globally under all scenarios (solid green and yellow lines in Fig 7). Notably, projected changes in soil moisture (Fig 6B) and solar radiation (Fig 6C) showed contrasting spatial patterns. Areas that gained suitable days because of water availability also lost days because of solar radiation, and vice versa; this could be explained by coupled dynamics between rainfall and cloud cover (Hernes 2015).

Plant growth is strongly mediated by the extent to which multiple interacting climate variables remain within suitable conditions. When looking at the interaction between temperature and solar radiation, we found that the number of suitable plant growing days will decline more so than either variable independently (5%, 9%, and 29% under RCP 2.6, RCP 4.5, and RCP 8.5, respectively; dashed yellow lines in Fig 7). This steeper decline is driven mainly by patterns at high latitudes, where gains in suitable plant growing days due to higher temperatures are offset by the fact that those places remain limited by light (compare the intensity of blue colours in Fig 6A and 6F). In contrast, the interaction between temperature and soil moisture resulted in a smaller reduction in suitable plant growing days than the losses due solely to temperature (0%, 5%, and 19% under RCP 2.6, RCP 4.5, and RCP 8.5, respectively; dashed blue lines in Fig 7). This smaller decline is driven mainly by patterns in arid regions (e.g., northern Africa, Australia, and the Middle East), where losses in suitable plant growing days due to higher temperature are reduced because those locations are already limited by water availability (compare yellow- and white-colored areas in Fig 6A and 6D).

Changes in suitable plant growing days due to the interaction between solar radiation and soil moisture were minimal (-2%, 0%, and 2% under RCP 2.6, RCP 4.5, and RCP 8.5, respectively; dashed purple lines in Fig 7), although there was considerable spatial variability (Fig 6E) due to the coupling between rainfall and cloud cover. When looking at the interaction among all three climate variables, we found that the global average number of suitable days still decreased under RCP 8.5 but less so than when temperature was considered alone or in interaction with solar radiation or soil moisture (-2%, 1%, and 11% under RCP 2.6, RCP 4.5, and RCP 8.5, respectively; dashed red lines in Fig 7). Gains and losses in suitable plant growing days due to projected temperature changes alone are lessened because some regions are already limited by either solar radiation (reducing gains at high latitudes) or water availability (reducing losses in arid regions). However, there is still an overall loss in suitable plant growing days, with some regions facing unsuitable conditions for multiple reasons. In addition to fewer plant growing days, unsuitable plant climate conditions will occur sporadically throughout the year, as indicated by our metric of continuous suitable plant growing days. We found that the longest uninterrupted number of days when all three climate variables remained within suitable climate ranges reduced considerably under RCP 4.5 and RCP 8.5 (5%, 13%, and 35% under RCP 2.6, RCP 4.5, and RCP 8.5, respectively; solid red lines in Fig 7).

While some areas at high latitudes (most noticeably in Russia, China, and Canada) will gain days with suitable conditions in all three climate variable (Fig 6G,), many other areas will actually become limited by multiple climatic variables as shown in figure 6 below:

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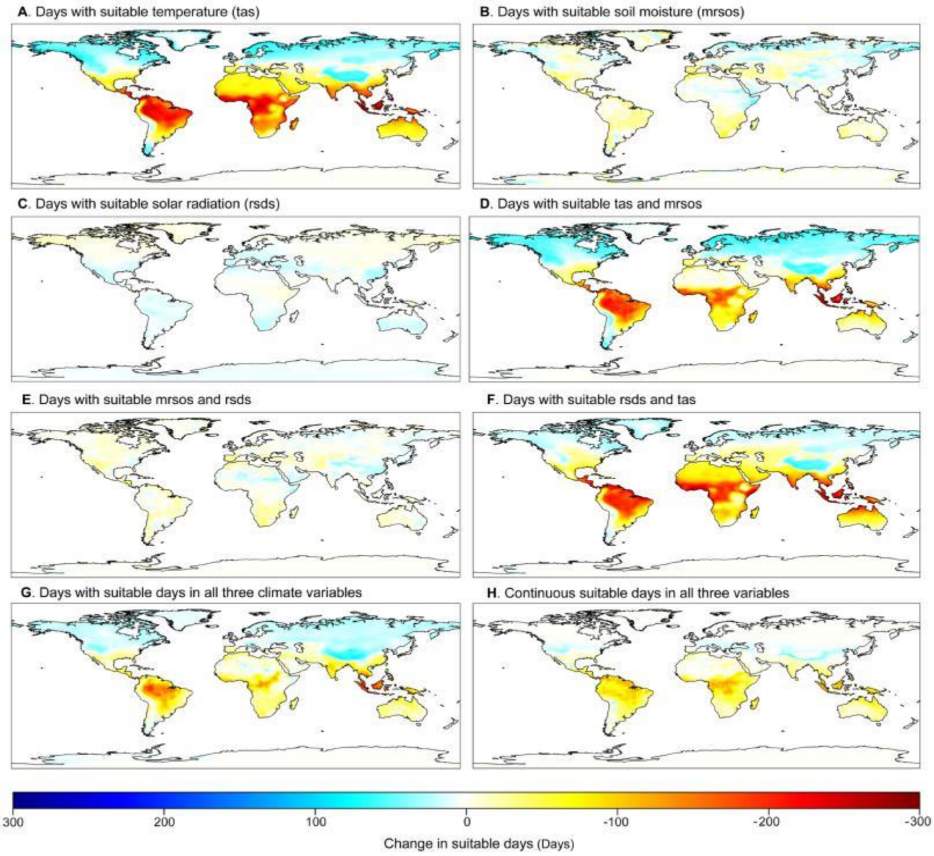

Fig 6. Spatial changes in projected suitable days for plant growth. Changes between future (i.e., the average from 2091 to 2100) and contemporary (i.e., the average from 1996 to 2015) number of days with suitable climatic conditions for plant growth under RCP 8.5 The map outline was obtained from the Central Intelligence Agency (CIA) World Databank (https://www.evl.uic.edu/pape/data/

For example, areas across the Sahel that are already limited by water availability will become increasingly limited by high temperatures by 2100 (Fig 6). The above results highlight the risk for synergistic responses and concerns over biological and societal adaptations given the suite of physiological traits and social capacity needed to cope simultaneously with future changes in several climate variables.

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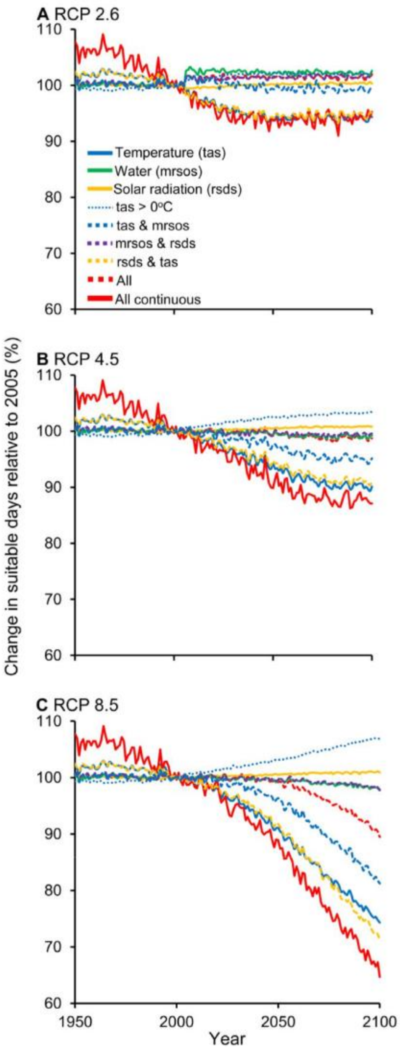

Source: *IPCC Report 2005*

Fig 7. Global average changes in projected suitable days for plant growth. These plots illustrate the global average number of suitable plant growing days relative to contemporary values.

Reductions in the number of days with suitable climate conditions for plant growth also underscore an internal discrepancy of Earth System Models: while these models project dramatic enhancements of NPP (Hernes et al 2015). Our results show multiple climate variables becoming limiting for plant growth, particularly in tropical areas, which could result in considerable reductions in future as shown in figure 7 above. This discrepancy likely reflects an overemphasis of CO_2 fertilization in modelling NPP while failing to account for the limiting roles of other climatic variables and disturbances (Hernes et al 2015).

Furthermore, reductions in plant growth due to unsuitable growing days could lead to feedbacks whereby climate change is even more extreme, leading to even less suitable condition for plant growth. The fact that unsuitable climatic conditions will occur more sporadically throughout the year highlights the potential for extreme events (e.g., heat waves

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or drought) to truncate the growing period, which may impair plant growth and even cause mortality. Zachos et al., (2008) recently concluded that "climate extremes can lead to a decrease in regional ecosystem carbon stocks and therefore have the potential to negate an expected increase in terrestrial carbon uptake," further highlighting an important research area for improvement of Earth System Models.

Most of the world's ecosystems and cultivated areas will be negatively affected by changes in the number of suitable growing days if climate change continues, possibly triggering climate feedbacks. Tropical ecosystems in particular (e.g., broadleaf evergreen forests; Fig 8 will lose suitable growing days due to temperatures exceeding the upper limit of the thermal range in combination with water failing to meet plant growth requirements.

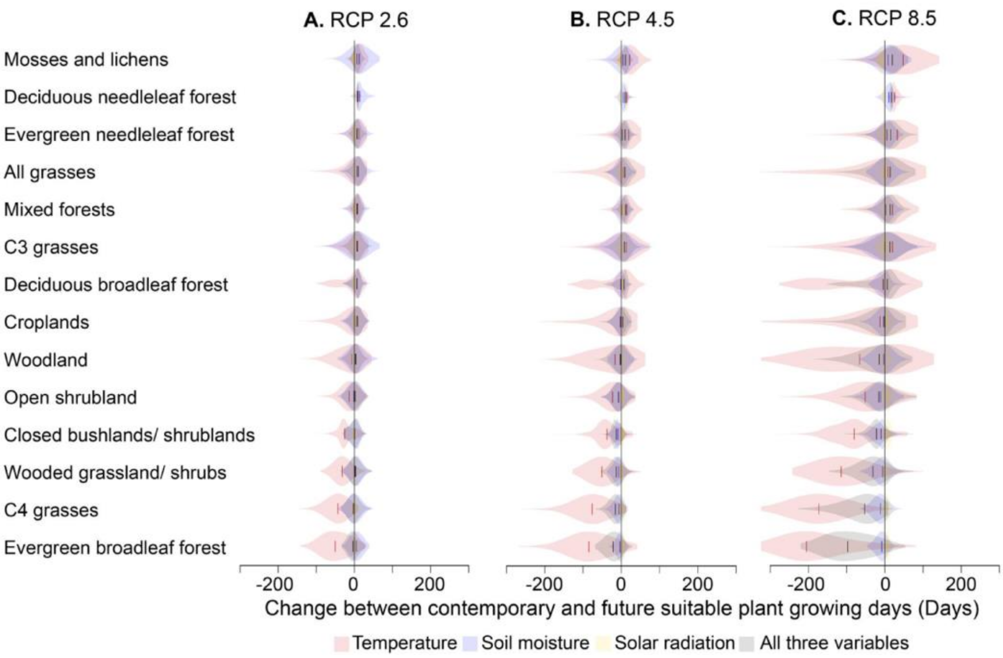

Fig 8. Biological exposure to projected changes in suitable plant growing days. Violin plots show frequency distributions of projected change between future and contemporary suitable plant growing days for all areas covered by each ecosystem; vertical colored lines indicate global median change for the given ecosystems. These plots are simply the overlay of our plant suitable days (data are provided in S2 Data) for areas of different land uses: (http://webmap.ornl.gov/wcsdown/wcsdown.jsp?dg_id=10006_1

Losses in suitable plant growing days can translate into losses of food, fibre, fuel, and associated jobs and revenue, with potentially negative effects in countries with high reliance on those goods and services, particularly those with minimal capacity to adapt.

Land constraints under current climate

The AEZ land-resources inventory allows a characterization of various regions according to the prevailing environmental constraints. A soil and terrain constraint classification has been formulated and has been applied to each grid-cell of the land-resources inventory, covering all land excluding Antarctica. The constraints considered include: terrain-slope, soil depth, soil

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fertility, soil drainage, soil texture, and soil salinity/sodicity. Climate constraints are classified according to the length of periods with cold temperatures and moisture limitations.

Table 2: Severe environmental constraints for rain-fed crop production (reference climate, 1981–2010).

Region	Total extents (10^6 ha)	Land with severe constraints for rain-fed cultivation of crops: Total with constraints (10^6 ha)	Total with constraints (%)	Too cold (%)	Too dry (%)	Too wet (%)	Too steep (%)	Poor soils (%)
North America	2,139	1,529	71.5	35.9	14.0	0.0	3.2	18.5
Eastern Europe	171	31	18.0	0.0	0.0	0.0	3.0	15.0
Northern Europe	173	78	45.2	18.0	0.0	0.0	2.5	24.6
Southern Europe	132	58	44.1	0.7	0.2	0.0	20.2	23.1
Western Europe	110	32	28.9	0.6	0.0	0.0	10.3	18.1
Russian Federation	1,677	1,140	68.0	44.5	1.9	0.0	1.9	19.7
Central America & Caribbean	271	140	51.7	0.0	27.7	0.4	15.0	8.7
South America	1,778	1,101	61.9	0.5	10.6	6.6	3.2	41.0
Oceania & Polynesia	848	630	74.3	0.1	58.6	3.9	1.2	10.5
Eastern Africa	888	462	52.1	0.0	27.0	0.0	3.1	22.0
Middle Africa	657	387	58.9	0.0	12.9	0.2	0.5	45.3
Northern Africa	547	500	91.3	0.0	88.0	0.0	2.2	1.0
Southern Africa	266	200	75.3	0.0	58.7	0.0	6.5	10.1
Western Africa	632	464	73.3	0.0	50.6	0.0	0.1	22.7
Western Asia	433	364	84.2	0.0	74.2	0.0	6.2	3.7
Southeast Asia	445	234	52.6	0.0	0.0	25.0	11.5	16.1
South Asia	668	361	54.1	2.0	34.7	0.0	10.6	6.8
East Asia & Japan	1,152	776	67.4	16.3	26.4	0.2	12.0	12.4
Central Asia	414	372	89.8	2.5	75.7	0.0	4.8	6.7
Developed	5,231	3,478	66.5	29.6	15.8	0.1	3.1	17.9
Developing	8,168	5,381	65.9	2.7	33.3	3.2	5.6	21.0
World	13,400	8,859	66.1	13.2	26.5	2.0	4.6	19.8

Note: Columns are mutually exclusive and the order in which constrains are listed defines a priority ranking for areas where multiple severe constraints apply. For instance. Land with very poor soil conditions in the arctic is shown as “too cold” and listed as having sever soil constraints.

On the basis of available global soil, terrain, and climatic data, the AEZ assessment estimates that under current climate conditions, some 8.9 billion hectares of land – about two-thirds of the Earth’s surface – suffer severe constraints for rain-fed crop cultivation. An estimated 13% is too cold, 27% is too dry, 2% is too wet, 5% is too steep, and 20% has very poor soils which ultimately will affect plant growths generally.

Impact of Climate Change on Cereal Production

The dynamic impact of climate change on the production of cereals, resulting both from changes in land productivity as well as economic responses of actors in the system, is summarized in Table 3

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Table 3. Impact of climate change on direct human cereal consumption, by developing region and climate model projections, in 2080 (% changes from respective reference projection).

	HadCM3				CSIRO			CGCM2		NCAR	
	A1FI	A2	B2	B1	A2	B2	B1	A2	B2	A2	B2
World	−3.4	−2.4	−1.4	−1.6	−2.5	−2.5	−2.4	−1.5	−0.4	0.7	0.7
Developing	−3.7	−2.6	−1.5	−1.8	−2.8	−2.7	−2.7	−1.6	−0.5	0.7	0.8
Africa	−2.8	−3.0	−1.1	−1.1	−1.8	−1.2	−1.1	−1.2	−0.1	0.0	0.9
Latin America	−2.0	−2.1	−0.5	−0.6	−1.2	−0.9	−0.5	−0.6	0.5	0.5	1.1
Southeast Asia	−3.9	−4.2	−3.0	−2.7	−2.5	−3.1	−3.3	−1.5	−1.2	−0.4	−0.6
Centrally Planned Asia	−4.8	−0.7	−0.2	−1.3	−4.3	−4.0	−4.2	−2.5	−0.2	2.4	2.4
Asia	−4.2	−2.5	−1.8	−2.2	−3.4	−3.5	−3.6	−2.0	−0.8	1.0	0.7

The model results present a fairly consistent pattern of response in regional cereal production to climate change. At global level, taking into account plant growth and economic adjustment of actors and markets, cereal production falls within 2% of the results for the respective reference simulations without climate change. Again, aggregation produces deceivingly small numbers. Developing countries consistently experience reductions in cereal production in all climate scenarios. Negative changes of 5–6% are most pronounced in simulations based on CSIRO climate projections. In this case, production moves to developed regions, notably North America and the Former Soviet Union, where increases of 6–9% are observed. The most significant negative changes occur in Asian developing countries, where production declines in all scenarios, ranging from about 4% decreases for CGCM2 and NCAR climate projections to reductions of 6–10% for HadCM3 and CSIRO

IMPLICATIONS FOR POLICY AND RESEARCH

Most of the world's ecosystems and cultivated areas will be negatively affected by changes in the number of suitable growing days if climate change continues, possibly triggering climate feedbacks as earlier stated Two current trends are considered to continue to dominate the agenda for agricultural policy in Europe during the first part of the 21st century. These are (1) the change to market economy and resulting increasing efficiencies and productivity in the agriculture of the former Soviet Union and eastern Europe, and (2) the continued trade liberalisation enforced by institutions like the world trade organisation, which from 1995 have included agriculture in the liberalisation efforts. These changes along with the reform of the EU CAP during the 1990s has considerably reduced the budgetary costs as the driving force in EU's agricultural policy (Matthews, 2021). This means that resources previously tied up in price support can now be made available to be invested in environmental schemes/research (Potter and Goodwin, 2020).

In addition to these current trends, European agricultural policy will need to consider support/research for the adaptation of European agriculture to climate change. This may be done by encouraging as much as possible the flexibility of land use, crop production, farming systems and so on. This would be feasible utilising the main agricultural resources (Table 4). In some cases such adaptation measures would make sense without considering climate change, because they help to address current climate variability. In other cases, the measures must be implemented in anticipation of climate change, because they would be ineffective if

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implemented as a reaction to climate change (Smith and Mathews (2021). Policy should include aspects related to both adaptation and mitigation. Parts of the agricultural land may be used for carbon storage and substitution of fossil fuel, and there is a large scope for reducing greenhouse gas emissions from agriculture (Potter and Goodwin, 2020).

Policies supporting plant growth and adaptation of agriculture to climate change may conflict with the current rigid structures of the EU CAP. Much of the financial support in the CAP is currently based on either the 1992 arable area or on country based quotas of livestock production. As climate change will affect the agricultural productivity differentially in various European regions, this will create an additional incentive to change the CAP towards a more flexible system, which is less dependent on regional production capacities.

European agricultural policy increasingly focuses on multifunctionality as its target and its organising principle (Tait,, 2020). The concept of multifunctionality requires different interpretation and variable balance among the environmental, social and economic functions in different European regions. In fertile areas and under favourable climatic conditions, priority will need to be given to production, but regulations must ensure that negative external environmental impact is kept within acceptable limits. In less fertile areas or areas with difficult climate, priority has to be given to financial support for the environmental and social functions of farming systems.

Table 4 Suggested resource based policies to support SSA adaptation of agricultural growth to climate change (modified from Easterling, et al. (2020).

Resource	Policy
Land	Reforming agricultural policy to encourage flexible land use. The great extent of Europe cropland across diverse climates will provide diversity for adaptation
Water	Reforming water markets and raising the 6alue of crop per volume of water used to encourage more prudent use of water. Water management, that already limits agriculture in some regions, is crucial for adapting to drier climate
Nutrients	Impro6ing nutrient use efficiencies through changes in cropping systems and de6elopment and adoption of new nutrient management technologies. Nutrient management needs to be tailored to the changes in crop production as affected by climate change, and utilisation efficiencies must be increased, especially for nitrogen, in order to reduce nitrous oxide emissions
Agrochemicals	Support for integrated pest management systems (IPMS) should be increased through a combination of education, regulation and taxation. There will be a need to adapt existing IPMS's to the changing climatic regimes
Energy	Impro6ing the efficiency in food production and exploring new biological fuels and ways to store more carbon in trees and soils. Reliable and sustainable energy supply is essential for many adaptations to new climate and for mitigation policies. There are also a number of options to reduce energy use in agriculture
Genetic Diversity	Assembling, preser6ing and characterising plant and animal genes and conducting research on alternati6e crops and animals. Genetic

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	diversity and new genetic material will provide important basic material for adapting crops species to changing climatic conditions
Research Capacity	Encouraging research on adaptation, de6eloping new farming systems and de6eloping alternati6e foods. Increased investments in agricultural research may provide new sources of knowledge and technology for adaptation to climate change
Information System	Enhancing national systems that disseminate information on agricultural research and technology, and encourages information exchange among farmers. Fast and efficient information dissemination and exchange to and between farmers using the new technologies (e.g. internet) will speed up the rate of adaptation to climatic and market changes
Culture	Integrating en6ironmental, agricultural and cultural policies to preser6e the heritage of rural en6ironments. Integration of policies will be required to maintain and preserve the heritage of rural environments which are dominated by agricultural practices influenced by climate

CONCLUSION AND RECOMMENDATION

Our study adds to the understanding of projected changes in climate suitability for plant growth and its implication for policy and research, highlighting where ecosystems and human populations could be more vulnerable to such changes. Although our study confirms a benefit of ongoing climate change on plant growing conditions at higher latitudes because of fewer freezing days, this considerably underestimates the full extent of consequences of projected climate changes, particularly under business-as-usual projections. Consideration of an upper thermal limit and interactions with plant growth thresholds in additional climatic variables resulted in the opposite trend: global decreases in the number of suitable plant growing days.

While maize yields have steadily increased in over 70 % of maize growing areas, in SSA maize yields remain the lowest in the world and have stagnated since the early 1990s (Collier, et al. 2008). Accumulating evidence of climate change in SSA. Suggests maize yields will decrease in many regions without the development of more climate resilient maize systems Adaptation to climate change will require cross-disciplinary solutions (Hodson, et al.2010) that include the development of appropriate germplasm and mechanisms to facilitate farmers’ access to the germplasm.

Thresholds could change either at the species level through genetic adaptation at the community level through replacement of species with those that are more tolerant today or those that have greater adaptive capacity. It would be projected that more varied ecosystems will have bigger capacity to deal with projected unsuitable climates compared to monoculture systems (i.e., more varied ecosystems should have a greater variety of thresholds. This highlights the vulnerability of many agricultural systems and associated human vulnerability to future climatic changes, as basic adjustments to farming practices.

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It should be noted that a major source of the world's productivity includes freshwater and marine plants, which could not be incorporated into the scope of this study because they are not limited by the same climatic conditions (e.g., soil moisture) as terrestrial NPP. Our approach could be replicated for those systems using the climatic variables that limit their productivity. This would represent another interesting further study.

RECOMMENDATIONS

Recommendation of climate change effect on plants include both ex-ante and ex-post risk management options (Cook et al.2012). The following are thus recommended:

1. Enacting a law to stop anthropogenic activities like indiscriminate burning of bushes, deforestation, industrial and vehicles emission standard.
2. Afforestation programs should be vigorously pursued.
3. Expansion – farmers increase income or resources by their lands, or their herd size. Expansion may come about through the distribution of new lands via land reform, the accumulation in fewer hands of land abandoned by migrating farmers, or through the clearing of previously unused land.
4. Broadening – farmers expand into new or existing market opportunities in order to increase income or decrease income variability. This may include the cultivation of new products and on-farm processing to add value to an existing product. In the case of Southern Africa, this may mean switching from maize to more heat- and drought-tolerant crops such as sorghum and millet (Burke et al. 2009). However, while both crops have shorter growing periods and require less water than maize, farmers prefer to grow maize.
5. Departure from agriculture takes place when farmers work in another farming system or pursue a non-farming life-style. Migration is a means of coping with climate variability (Adger et al. 2003).

The aforementioned recommendation are likely to mitigate the detrimental impacts of climate change but in terms of farmers' adaptation strategies, plant breeding will continue to play a critical role.

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