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Assessing Climate Change Projections and Impacts on Central Malawi's Maize Yield: The Risk of Maladaptation

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Abstract

Malawi is listed as a Low-Income Food-Deficit Country (LIFDC) by the United Nations (UN), with high levels of poverty, malnutrition, and undernutrition. The maize grown in the Central Region of Malawi represents approximately a quarter of the total Malawian population's calorie intake, is a large source of local income, and a significant contributor to the country's Gross Domestic Product (GDP). While maize has been shown to be more resilient to climatic changes than many other grain crops, the

Useful Abbreviations:

CORDEX: Coordinated Regional Climate Downscaling Experiment
FAO: Food and Agriculture Organisation of the United Nations
FISP: Farm Input Subsidy Programme
GDP: Gross Domestic Product
GNI: Gross National Income
HI: Harvest Index
LIFDC: Low-Income Food-Deficit Country
Pr: precipitation rate
RCMs: Regional Climate Models
RCPs: Representative Concentration Pathways
Tas: mean surface air temperature
TasMax: maximum surface air temperature
TasMin: minimum surface air temperature
UN: United Nations

predominantly rain-fed maize grown in Central Malawi has experienced many shocks from severe weather events in the past. Using the ensemble mean of 20 Regional Climate Models (RCMs), this study shows that temperatures in Central Malawi are projected to increase from the 1971-2000 baseline by between 1.4 and 1.6°C by 2035 and 1.9 and 2.5°C by 2055 under Representative Concentration Pathways (RCPs) 4.5 and 8.5 respectively, but precipitation projections are more uncertain. Using the UN Food and Agriculture Organization's (FAO) AquaCrop model, this study assesses the impact of future warming and three precipitation scenarios on two cultivars of maize planted on three separate dates in Central Malawi's summer planting season. The results indicate that if precipitation levels follow the ensemble average or maximum projection, then moving to a later planting date and a slower-developing cultivar may result in increasing yields compared to the baseline scenario. However, under a minimum precipitation projection, the results are less positive, with decreasing yields seen for both cultivars and all planting dates. The uncertainty around future precipitation therefore poses a significant risk of maladaptation and highlights the need for more robust precipitation projections in the area before climate model outputs are used as a primary driver for decision-making in Central Malawi's maize cultivation.

Keywords

CORDEX, Sub-Saharan Africa, Crop Yield, Food Security

1. Introduction

Globally maize provides almost seven percent of the world's calorific intake by way of direct consumption (FAOSTAT, 2018a), but as it is also the largest source of livestock feed grain, it is indirectly responsible for much more (CGIAR, 2016). It is the staple crop for many food insecure populations, and an important source of calories for people living on less than US $2 per day (ibid.). With an ever-increasing global population, and the consumption of animal-based food products and biofuels on the rise, the demand for maize is expected to double by 2050 (Hubert et al., 2010). However, recent studies suggest that climate change will lead to declining maize yields and price volatility, exacerbating existing challenges around food security, poverty and malnutrition (Zampieri et al., 2019, Tigchelaar et al., 2018).

Like much of the developing world, maize is currently, and has historically been, the main food crop in Malawi (see Figure 1), and it is grown by 97% of smallholder farmers (NSO, 2005). Almost half of the calorie intake in Malawi is met by the direct consumption of maize and maize products (see Table 1), the majority of which is domestically grown in the Central Region using rain-fed production (Arya et al., 2005). Agriculture is the main source of income in Malawi, with over three-quarters of Malawi's population employed in the sector, and over a third of Malawi's Gross Domestic Product (GDP) related to agricultural activity (FAO, 2017, CIA, 2018). Within this sector, maize has been the largest contributor to Malawi's gross agricultural production value in 37 of the last 56 years (1961-2016), coming second 16 times, and third only three times (FAOSTAT, 2018b).

While the Malawian government and many food aid organisations have been concentrating on improving domestic agricultural production and food security in the country for more than a decade (IFPRI, 2018), the Food and Agriculture Organisation of the United Nations (FAO) still classifies Malawi as a Low-Income Food-Deficit Country (LIFDC) (FAO, 2018b). Climatic, political, and governance shocks have had a negative effect on developmental progress and resulted in minimal poverty alleviation, particularly in rural areas (IMF, 2017). Severe droughts such as those experienced by the region in

1992, 1994, 1997, 2001, 2005 and 2016 have had a significant negative impact on the country's economy, food supply, and poverty levels (see Figure 2) (World Bank, 2016, World Bank, 2017). The relative lack of diversity in the calorie share, the share of economic and household income from agriculture, and the vulnerability of that agriculture to climatic changes has meant that Malawi is often reliant on high levels of international aid. For example, crop losses due to the 2005 drought meant that 40 percent of the population required immediate food aid (Giertz et al., 2015).

The Malawian government introduced the Farm Input Subsidy Programme (FISP) after the 2005 drought which helped increase crop production and improve national food security mainly through improved access to fertilisers, however it is unlikely that this measure alone will be able to maintain food security in a changing climate (Msowoya et al., 2016). With limited finances and technology to cope with changes, and much of the economy, employment and food supply reliant on a predominantly rain-fed agricultural sector, Malawi is highlighted as being particularly vulnerable to future climate change (Minot, 2010, FAO, 2017, Giertz et al., 2015).

Under all future climate projections, the surface temperatures in Malawi are expected to rise, but precipitation projections are less certain (Mittal et al., 2017, World Bank Group, 2019). While maize has an optimal growing temperature range that is higher than many other globally important grain crops (Sanchez et al., 2013), it is still sensitive to changes in maximum daily temperatures (Tebaldi and Lobell, 2018, Lobell et al., 2013). Upper temperature threshold exceedances result in reduced photosynthesis and increased evapotranspiration rates, and therefore increased water demand (Crafts-Brandner and Salvucci, 2002, Zampieri et al., 2019). Furthermore, higher temperatures hasten the transition between phenological phases and reduce crop yields (Tebaldi and Lobell, 2018). Maize is particularly vulnerable to temperature anomalies during the flowering and yield formation stages of development, as higher temperatures decrease pollen germination and lead to shortened kernel filling and yield development (Zampieri et al., 2019, Gourdji et al., 2013). Maize is also drought sensitive, particularly early-on in crop development. A lack of water in early development can cause delays in crop flowering, reduced photosynthesis and decreased yield (Zampieri et al., 2019). Furthermore, low soil moisture tends to exacerbate the temperature stresses described above (Lobell et al., 2013).

Based on climate change projections for Sub-Saharan Africa, various studies have indicated vulnerability for maize's future crop productivity in the region, with maize yields expected to decrease in the 21st century (Gachene et al., 2015, Challinor et al., 2014). For Malawi more specifically, some previous research has gone into quantifying the impact that climate change will have on domestic maize yields (Saka et al., 2012, Zinyengere et al., 2014, Fiwa, 2015, Msowoya et al., 2016, Stevens and Madani, 2016, Olson et al., 2017). The results from these studies vary significantly, with some projecting a decrease in maize yield of up 14% and others a projected increase of up to 25% by 2050. The wide range in results stems from the assumptions made, both in terms of future climate and in crop modelling. Most of the studies used models calibrated for one cultivar of maize with one planting date. Fiwa (2015) assessed the impact on three different cultivars (early, intermediate and late maturing), but only one planting date and highlighted the need to research the impact of changing planting dates on the crop yield under future climate scenarios. Zinyengere et al. (2014) on the other hand looked at one cultivar and two planting dates but only under one climate projection. All these previous studies highlight the importance of understanding the variables that will impact maize's yield response to climate change, as making choices on incomplete information poses a risk of maladaptation. This paper therefore aims to determine the impact of projected climate change on the yield of two different maize cultivars planted on a variety of dates during the summer planting season in the Central Region of Malawi, and to examine the utility of this in informing cultivation practices and potential risks of maladaptation. The Central Region produces the majority of the food in Malawi and this boundary represents over a quarter of the Malawian population's calorie intake (FAOSTAT, 2018a, Arya et al., 2005).

2. Climate Change Projections

To understand the impact of climate change on maize yields in Central Malawi, it is first important to get a clear understanding of how the climate is currently predicted to change. Here we assess the change in projected temperature, precipitation, and evapotranspiration rate for the 2035 (2020-2049) and 2055 (2040-2069) climates. These time horizons have been chosen as they are both short-term enough to be relevant to current farmers, consumers, and policy makers, and long enough to allow for adaptation to take place.

2.1 Climate Modelling Methodology

To project Malawi's climate into the future, we make use of 20 RCMs produced by different organisations within the Coordinated Regional Climate Downscaling Experiment (CORDEX) initiative (see Table 1 in the Supplementary Information, found in the author's GitHub directory[1]). The CORDEX initiative sets a standard grid, domain size, experiment protocols, and data format allowing for direct comparison of the model outputs (Giorgi et al., 2009, Nikulin et al., 2012). Within this framework, only models which were publicly available and provided projections for Representative Concentration Pathways (RCPs) 4.5 and 8.5 were selected[2]. All the RCMs are atmospheric models produced within the defined CORDEX-Africa domain, they provide data on a daily time scale, and have a 0.44-degree (approximately 50km^2) resolution.

An evaluation of the ability of these RCMs to hindcast daily minimum, maximum and mean temperature (TasMin, TasMax, and Tas respectively) in Malawi found that they are not able to adequately simulate absolute temperatures, however the trending change in temperature correlated well (Warnatzsch and Reay, 2019). To take this in to consideration in this study, the methods used by UKCP09 was applied to re-baseline the temperature and precipitation data (UKCP, 2014). This

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[1] Erika Warnatzsch GitHub directory: https://github.com/ErikaWarnatzsch/Malawi-Future-Climate-Modelling-Assessment

[2] At the time of writing there was one additional RCM available that met these criteria, HIRHAM5_NorESM1-M, however this model has been excluded from this study. Based on the findings of Warnatzsch and Reay (2019), this RCM is a major outlier and does not simulate Malawi's temperature or precipitation well.

methodology involves using a 30-year average from station and satellite observed data, in this case 1971-2000, and adding to that the difference between the climate variable output for the time-period of interest and the hindcasted 1971-2000 average from the CORDEX models. The observed data used for this re-baselining are detailed in Table 2 of the Supplementary Information.

The CORDEX-Africa models do not have an output for reference evapotranspiration, and an adequate observed database for historical reference evapotranspiration rates could not be found for Malawi. As such, the historic and projected reference evapotranspiration data were determined through calculation. To calculate the reference evapotranspiration data, the FAO's Penman-Monteith (FPM) method was applied (Allen et al., 1998a, Allen et al., 1998b). Full details of the calculations applied can be found in the Supplementary Information. This methodology was tested for application in Malawi by Wang et al. (2011) and Southern Malawi by Ngongondo et al. (2012) and deemed to be appropriate for use.

While half of the models use a 366-day calendar (include leap-days), seven use a 365-day calendar and three use a 360-day calendar (assumed all months are 30 days). To create the daily profiles used here, it was necessary to make all the calendar formats the same. There is no standard method to do this, however the crop model used requires a 365-day year. Therefore, we took the decision to add a 31st day to May, July, August, October and December for the 360-day calendars and remove February 29th from all the 366 and 360-day models. No 31st day was added for January or March, as the extra days from February accounted for this. The data for these additional days were created by using an average of the data from the five days before and five days after the missing date.

Limited by the resolution of the models, and the need to use a rectangular boundary, the assessment includes spatial data that are larger than the actual geographical boundary of the Central Malawi region, as shown by the grey shaded areas in Figure 3.

Analysis by Warnatzsch and Reay (2019) found that the RCM model outputs for precipitation are highly divergent and not well correlated to observed precipitation levels. As such, we recommended that a range of future precipitation scenarios be used for impact assessment and adaptation planning for the future food supply chain in Malawi. The current study will therefore assess impacts using three future scenarios based on the ensemble maximum, minimum, and mean projections for precipitation rate in Malawi. Warnatzsch and Reay (2019) also found that the ensemble average better represented the temperature records of Malawi than individual model simulations. Therefore, these three precipitation scenarios will be used in combination with ensemble average mean, minimum and maximum daily temperature projections, and calculated reference evapotranspiration rates. Analysis of the results was performed using a Python interface. Within the interface, the numerical mathematics and graphical plotting were produced using a variety of open source Python libraries and packages. The code used for each assessment can be found in the author's GitHub repository.

2.2 Climate Change Projection Results

Malawi's climate is classified as sub-tropical and has distinct seasons: a warm and wet season from October to April and a cooler, dry season from May to September. This seasonality is projected to continue under both RCP 4.5 and RCP 8.5, although all seasons are expected to get warmer with annual average temperatures increasing by 1.4 and 1.6°C by 2035 and 1.9 and 2.5°C by 2055 (see Table 2 for details). For both time periods and scenarios, the temperature increase is seen to be largest in the autumn months (March-May), as seen in Figure 4. Overall, based on the calculation methods, annual reference evapotranspiration rates in Central Malawi are projected to remain relatively stable, only showing a slight increase from the 1971-2000 baseline in both future time periods and RCP scenarios (Table 3).

Three scenarios were run for projected precipitation: minimum projection, ensemble mean and maximum projection (Table 3). The minimum RCM projection has annual precipitation decreasing by approximately half from the 1971-2000 baseline, while the ensemble mean shows a much smaller decrease of only 3-4%. The maximum RCM projection has precipitation increasing by between a fifth and a quarter compared to the 1971-2000 baseline. Figure 4 show that there is largest agreement in the models for precipitation during the dry season, with larger variation in the wet season in both time periods and scenarios.

3. Impact on Maize Yield

There are multiple crop models available, each with their own characteristics and applications (Di Paola et al, 2015). While the use of crop models does have limitations, they are still useful tools for determining the likely impact of specific changes on a crop (Boote et al., 1996). In this study we are interested in determining the impact of various potential future climate scenarios on the yield of two maize cultivars in Central Malawi. For this purpose, we have chosen to use the FAO's crop growth model, AquaCrop. AquaCrop is a crop growth model which is specifically built to evaluate the yield response of a variety of crops to different environmental factors and crop management techniques (FAO, 2018a). While there are many variables that can be altered and calibrated for local specificity within the model, it is also possible to leave some aspects as 'default' to focus in on the impact of changing one variable or category, in our case, the climatic conditions. This ability to both calibrate the model where necessary (e.g. the climatic, crop and soil characteristics), but also keep the complexity to a minimum makes AquaCrop an ideal tool for the purposes of this study.

Various studies have assessed AquaCrop's sensitivity to climatic changes and its suitability for use in modelling yield response at a regional scale for rainfed maize (for example, Mebane et al., (2013), Akumaga et al., (2017), and Mibulo and Kiggundu (2018)). Fiwa (2015) assessed the ability of AquaCrop to simulate yield of rainfed maize in Central Malawi specifically and found a good correlation between observed data and simulated outputs. Stevens and Madani (2016) also evaluated AquaCrop's ability to simulate yields for maize in Central Malawi and found that, while the model overestimated yields in their study, it was still suitable for assessing relative change. As such, this model is deemed appropriate for use in examining the potential effects of climate change on maize yields in Central Malawi, particularly if using relative change in yield rather than absolute values.

3.1 Crop Modelling Methodology

AquaCrop has been developed to be used at both the field and regional-scale (FAO, 2018a). When used at the regional-scale, as is the case in this study, a variety of climatic and environmental parameters must be identified for input into the model. These inputs help to calibrate both the crop and environmental factors to be as specific as possible to the region in question. The crop, soil, and climate files used in this study can be found on the author's GitHub repository.

A total of 13 climate scenarios were created to test the impacts of climate change on maize yields in Malawi (see Table 3 in the Supplementary Information). These scenarios were created using the models and data described in Section 2 above. The historical climate represents the 1971-2000 period using daily data adjusted from hindcasted ensemble RCM outputs for: minimum and maximum near-surface temperatures; minimum, mean and maximum precipitation rates; and calculated reference evapotranspiration rates. This historical climate used the default Mauna Loa CO_2 concentrations file that is provided by the AquaCrop Model. To represent future climate change, 12 climate scenarios were created. Half of the future climate scenarios use projections for RCP 4.5 and the other half RCP 8.5. For the CO_2 concentrations, these future climate scenarios use the AquaCrop IPCC RCP 4.5 or 8.5 files respectively. Within each of the two RCP scenarios, two time-periods were assessed, the 2035 climate (2020-2049) and the 2055 climate (2040-2069). The appropriate time-period and RCP scenario was used with adjusted ensemble RCM daily minimum and maximum temperatures, and calculated daily evapotranspiration rates. For each of these four future climates (two RCPs and two time-periods), three potential climate scenarios were created using ensemble minimum, ensemble mean and ensemble maximum precipitation rate projections.

To ensure that we were only analysing the impact of changing climate, rather than any other human-induced factors, we have assumed that no irrigation and no field management is used. The authors acknowledge that this will mean that the absolute output data will be biased by the assumed lack of human management, and that the relative changes will therefore only reflect the impact of climatic change on the crops (in reality some degree of management change is inevitable). According to Chavula (2012) the depth of the water table in Central Malawi is 15-25 meters below the surface. As this is too deep to influence crops, no groundwater is considered in the AquaCrop model. The soil in the majority of Central Malawi is described as a Sandy Clay Loam (Saka et al., 2003) so the analysis used the AquaCrop 'Sandy Clay Loam' file as a base to calibrate a new source file specific for Central Malawi. The calibration of this file is based on analysis carried out by Fiwa (2015) and is described in Table 4. It is worth noting however that, when tested for sensitivity, this soil calibration did not create a significant change to the yield simulations in the historic climate scenarios, or any of the average or maximum precipitation scenarios. The calibration did however have a significant impact on the output of some of the minimum precipitation scenarios and as such is a potential source of error (see Tables 4, 5 and 6 of the Supplementary Information).

The majority of maize grown in Central Malawi is rainfed and produced by smallholder farms for own use (Arya et al., 2005, FAO, 2015). The maize is planted via direct sowing with most of the maize in Central Malawi planted in the summer between the 15th of November and the 31st of December (Arya et al., 2005, FAO, 2010, Fiwa, 2015). For this analysis, three planting dates within this period were input into the AquaCrop model for analysis: November 15th, December 10th and December 30th. AquaCrop provides a default maize model and this has been shown to be effective at simulating yield changes to various climatic stresses (Heng et al., 2009). However, to better reflect the characteristics of the maize grown in Central Malawi, data from studies conducted in the area were used to better calibrate the model (see Table 5 and Table 6). As such, two maize crop models were calibrated to represent short and long growth cycle (fast- and slow-development) maize varieties that are typically grown in Central Malawi. The calibration of the crop files does create a significant impact on the output of the model and as such is also a potential source of uncertainty (see Table 7 of the Supplementary Information). For comparison purposes, the two varieties were given shared characteristics, with the times taken to reach each growth stage being the only differences. Table 5 shows the shared characteristics and Table 6 shows how the two varieties differ. These tables only show changes that can be input into AquaCrop, there are also some differences in characteristics that AquaCrop automatically calculates based on these inputs.

3.2 Crop Modelling Results

The results from AquaCrop indicate that the impact of projected climate change on maize yields is highly dependent on the precipitation scenario for both the slow- and fast-development cultivars, with the changing planting date giving mixed results. (see Table 7). Both cultivars show a decreasing yield in all future climate scenarios with minimum precipitation. While the fast-development cultivar generally shows a smaller yield decrease under the minimum precipitation scenarios with later planting dates, the reverse is true for the slow-development cultivar which shows larger yield decreases with later planting dates under a minimum precipitation scenario. Under the average or maximum precipitation scenarios, the future climates show a small increase or decrease in yield depending on planting date and cultivar. For the earliest planting dates, the maximum precipitation leads to a better yield outcome than the average precipitation scenario in all future scenarios, but for later planting dates, the yield outcome is the same for both the average and maximum precipitation scenarios. Under the average or maximum precipitation scenarios, the fast-development crop acts differently than under a minimum precipitation scenario, and the yield outcome is generally better when the crop is planted earlier in the season. Contrary to the minimum precipitation scenario, the slow-development crop has the best yield outcome with the latest planting date in all future scenarios with average or maximum precipitation.

Due to the timing of precipitation and planting, the three precipitation scenarios do not impact the amount of water available to the crops in all stages of development proportionally - as shown in Figure 5 for the slow-development cultivar (the equivalent figure for the fast-development cultivar is shown in Figure 1 of the Supplementary Information). As maize has a different sensitivity to water availability in each development stage, the timing of the precipitation has a large impact on the crop development and yield formation. Additionally, the change in precipitation scenario does not cause directlyproportional changes in the water content of the soil at the effective root zone of the plant, which further explains the yield response. This may be due to the type of soil in the region, timing of the precipitation, relatively stable evapotranspiration rates, response of the plant to rising temperature, and water uptake of the plant at different stages of development. For both the fast- and slow-development cultivars, the crop is exposed to less water availability in the effective root zone under the minimum precipitation scenario as compared to the baseline period in all stages of growth and future time periods. For both cultivars, under the minimum precipitation scenario, the largest decrease in water availability occurred for the middle planting date for the emergence and vegetative stages. However, the earliest planting date saw the largest decrease in water availability during flowering and yield formation. The average and maximum precipitation scenarios generally result in an increase in the water availability in all stages of the development for the both cultivars, with more availability under the maximum precipitation scenario than the average. It should be noted that in the water-sensitive flowering and yield producing stages (Manivasagam and Nagarajan, 2018), the increase under the average and maximum precipitation scenarios compared to the baseline period was generally largest with later planting dates, particularly for the slow-development cultivar, which may explain why the yield increases were largest in these scenarios.

To test how much of the yield change was a result of precipitation and how much was due to temperature, the crop model was run again using the same crop and soil calibration but using historic climatic data for all variables except either precipitation or temperature respectively. The results of these test runs are shown in Table 8 and Table 9. These indicate that, for both cultivars of maize, precipitation is the predominant factor in changing yields. Increasing temperature plays a small positive role for most planting dates in 2035 but, by 2055, the higher increase in temperature results in a negative yield influence in all but one scenario. The crop yields are more favourable under RCP 4.5 scenarios than RCP 8.5, and generally improved with planting at the latest time rather than the earliest. This is consistent with an analysis of the number of days which exceed the maximum temperature threshold for crop development, with only the earliest planting date showing exceedances, and the number of exceedances increasing for the high warming RCP scenario (see Table 8 of the Supplementary Information).

Overall, our analysis finds that Malawi's climate is expected to warm by around 2°C by the middle of the century, but that projections for precipitation are highly divergent. Modelled maize yields identified some potential yield increases for a slow-development cultivar under average and high precipitation scenarios by 2055, while yields of a fast-development cultivar decreased in all but two climate and planting date scenarios over this same period.

4. Discussion

Both the scale of relative change in the ensemble RCM mean precipitation rate and the large discrepancy between model outputs that we have found in the RCMs are consistent with the findings of other climate change projections for Malawi and Sub-Saharan Africa more broadly (e.g. Mittal et al. (2017), Niang et al. (2014)). Mittal et al. (2017) used 34 of the latest Global Climate Models (GCMs) for their projections of Malawi's climate and found that almost half showed changes in rainfall to be less than +/-5% by 2040, with the other half in disagreement as to whether the climate in Malawi will become wetter or drier. According to their study, the ensemble average of the GCMs showed a slight decrease in precipitation of around 2-4% by 2040, with a larger drying out seen in later time periods. This uncertainty in the projections highlights the need to assess multiple potential future precipitation scenarios, but also suggests that the extreme minimum and maximum precipitation scenarios used in this report are unlikely, with reality more likely to be closer to the average precipitation scenario.

The climate in the Central Region of Malawi is changing, and this is expected to have a mixed impact on maize yields in the coming decades. Under a minimum precipitation scenario, both cultivars show a large decline in yield under all future climate scenarios and planting dates. For the average and maximum precipitation scenarios, the direction of yield change is more reliant on the cultivar, time-period, RCP scenario, and planting date.

Through isolating the climatic variables in the crop model, it was possible to determine that future temperature levels play little role in the yield outcome of both maize cultivars in the short term. However, by 2055, the extent of the warming does start to play a larger negative role, particularly for earlier planting dates. Conversely, a reduction in precipitation does have a large negative impact on yields, while the increasing precipitation of the average or maximum scenarios only showed slight improvements in yield.

While our study suggests that planting later in the season and using slower developing cultivars may help improve yield outcomes in a warmer climate, these increasing temperatures will not happen in isolation. Importantly, other factors and their interactions with climate variables must also be considered before any planting advice is developed and certainly before it is applied. For example, Cairns et al. (2013) found that while the development of more climate resilient maize cultivars could lead to improved yield outcomes in Sub-Saharan Africa, this would not be successful without improved management systems and farmers gaining access to the necessary seeds. Switching from cultivars based on development length may also have other consequences, including changing the timing of and magnitude of climatic stresses, the absolute size of the yield, the uptake of soil nutrients, and vulnerability to pests and disease, all of which need to be considered. Without access to technological solutions such as irrigation, the uncertainty around precipitation levels may also make any change between these two varieties futile.

Cherry-picking a single future prediction and basing future planting decisions on this may lead to unintended negative outcomes due to uncertainty in the climatic projections and simplicity in the crop modelling. The importance of assessing a variety of crop types and planting dates, as well as the challenge of addressing the sensitivity of the soil and crop calibration in the models is highlighted by the high degree of variation found in the results of this and other studies (Saka et al. (2012), Challinor et al. (2014), Zinyengere et al. (2014), Gachene et al. (2015), Fiwa (2015), Msowoya et al. (2016), Stevens and Madani (2016) and Olson et al. (2017)). Previous studies indicate that maize yields may decrease by as much as 14% or increase by up to 25% under a changing climate, with the main differences between the studies being the cultivar calibration, climate scenario and planting date. The range of outcomes seen in these previous studies is echoed in our results although, due to the use of more extreme minimum and maximum precipitation scenarios and not just an ensemble average, the lower end of the range is more extreme. Furthermore, our results and the results of most previous studies base their findings on just one crop model type that is calibrated for a specific situation. Crop models, while very useful, do have limitations and these should be considered when determining the usefulness of their outputs for the research and policy community in Central Malawi and any other region they are applied to (Boote et al., 1996, Di Paola et al., 2015). In this case AquaCrop was deemed appropriate for use in examining the potential climate change impacts on two maize cultivars grown in Central Malawi, however these results do not necessarily translate into climate-smart application at an individual farm level. Changes in the crop model choice and calibration could cause the results to vary widely, and as such, crop models should be tested for applicability, and more local calibration will be required to develop and recommend robust climate change adaptation options. Real world application would also need to consider key interactive effects, such as soil fertility and management practices, which are not assessed in this paper.

Likewise, the projected impact of climate change on the volume and timing of precipitation in the studied region is highly uncertain and this too may lead to maladaptation when choosing maize planting dates and cultivars. This risk is echoed by Sutcliffe et al. (2016) who found evidence of potential maladaptation already taking place in parts of Southern Malawi, with farmers already switching maize cultivars due to perceived changes in rainfall. The disparity in future precipitation projections, combined with the more certain temperature projections, results in either a greatly negative or greatly positive impact on final maize yields. The sensitivity of Malawi’s main food source to precipitation highlights the need for more locally-calibrated crop models and higher resolution climate modelling to better inform adaptation measures. In the interim, improved access to short-term weather forecasting and early warning systems for extreme events, such as floods and droughts, is required, but this would not address the need for long term agronomic solutions and adaptation.

In the face of such uncertainty, technical solutions, such as the use of irrigation, could reduce the impact of changing precipitation patterns, particularly if the climate follows a scenario of declining precipitation. This could target soil moisture deficits in the more vulnerable growth stages of the maize to help improve yield outcomes. However, special care must be taken to ensure that future practices consider the whole system and do not waste already limited water and energy resources (USAID, 2013) or contribute to the land degradation and declining soil fertility already challenging the area (Vargas and Omuto, 2016).

In this study it was not possible to determine the impact of climate change on the yield of other main crops such as potatoes or cassava, or on a larger range of maize cultivars, or the growth of any of these crops in differing soil conditions, as the information required to effectively calibrate the crop model is not readily available. Diversifying the crops grown by smallholders in Malawi is highlighted as a significant and viable option for improving food security (Mango et al., 2018). Crop diversification could make the agricultural sector more stable and provide improved dietary diversity and nutrition (ibid.). However, there has been very little research into how climate change will impact other food crops in Malawi, and this will need to be understood to avoid farmers investing in potentially more vulnerable crop types or cultivars.

Assessing how climate change will impact the availability of food is key to determining future opportunities and risks. However, the vulnerability of the food system does not stop with yields. To get a more complete picture, further examination of the three other dimensions of food security and how they interact with climate change is required, namely: how the price of food will change the purchasing power (PP) of the population and therefore change access to the food; how food-borne diseases, pests and post-harvest food losses (PHL) will impact the safety and utilisation of food crops; and how interactions between ecosystems, transboundary impacts (e.g. water abstraction in

Tanzania) and the socio-economics of the agricultural sector threaten the wider stability of the system (Campbell et al., 2016, FAO, 2008).

5. Conclusions

Malawi currently faces large challenges with food security, and interventions will be required, with or without further climate change, to deal with issues around a lack of enough calories and a lack of sufficient diversity in nutrients (IFPRI, 2018). Climate change represents a further risk multiplier for an already-vulnerable agricultural sector and food supply system. Our study shows that use of existing climate projections coupled with a widely-used crop growth model (AquaCrop) has limited utility in terms of informing future maize growing decisions at the local scale in Central Malawi. Indeed, our analysis highlights the potential for maladaptation, where uncertainties in projected climate variables (especially precipitation) and lack of local scale model calibration could result in a choice of maize cultivars that reduces climate change resilience instead of enhancing it.

We recommend that investment be made into higher resolution climate modelling alongside greater accessibility of outputs, particularly around precipitation. This would allow for the projected climate impacts and associated uncertainties to be better incorporated into decision-making by policy makers, extension service providers, and the farmers themselves. More locally-specific studies on the climatic sensitivity of multiple cultivars of the main food crops for a variety of soil and farm management conditions are also required. This information could allow the creation of context-specific 'no regret interventions', targeted investments, and education programmes to allow both commercial and subsistence farmers to make sound and sustainable adaptation decisions in a changing climate.

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