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The Role of Crop Management Practices and Adaptation Options to Minimize the Impact of Climate Change on Maize (*Zea mays* L.) Production for Ethiopia

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Abstract: Climate change impact assessment along with adaptation measures are key for reducing the impact of climate change on crop production. The impact of current and future climate change on maize production was investigated, and the adaptation role of shifting planting dates, different levels of nitrogen fertilizer rates, and choice of maize cultivar as possible climate change adaptation strategies were assessed. The study was conducted in three environmentally contrasting sites in Ethiopia, namely: Ambo, Bako, and Melkassa. Future climate data were obtained from seven general circulation models (GCMs), namely: CanESM2, CNRM-CM5, CSIRO-MK3-6-0, EC-EARTH, HadGEM2-ES, IPSL-CM5A-MR, and MIROC5 for the highest representative concentration pathway (RCP 8.5). GCMs were bias-corrected at site level using a quantile-quantile mapping method. APSIM, AquaCrop, and DSSAT crop models were used to simulate the baseline (1995–2017) and 2030s (2021–2050) maize yields. The result indicated that the average monthly maximum air temperature in the 2030s could increase by 0.3–1.7 °C, 0.7–2.2 °C, and 0.8–1.8 °C in Ambo, Bako, and Melkassa, respectively. For the same sites, the projected increase in average monthly minimum air temperature was 0.6–1.7 °C, 0.8–2.3 °C, and 0.6–2.7 °C in that order. While monthly total precipitation for the Kiremt season (June to September) is projected to increase by up to 55% (365 mm) for Ambo and 75% (241 mm) for Bako respectively, whereas a significant decrease in monthly total precipitation is projected for Melkassa by 2030. Climate change would reduce maize yield by an average of 4% and 16% for Ambo and Melkassa respectively, while it would increase by 2% for Bako in 2030 if current maize cultivars were grown with the same crop management practice as the baseline under the future climate. At higher altitudes, early planting of maize cultivars between 15 May and 1 June would result in improved relative yields in the future climate. Fertilizer levels increment between 23 and 150 kg ha^{-1} would result in progressive improvement of yields for all maize cultivars when combined with early planting for Ambo. For a mid-altitude, planting after 15 May has either no or negative effect on maize yield. Early planting combined with a nitrogen fertilizer level of 23–100 kg ha^{-1} provided higher relative yields under the future climate. Delayed planting has a negative influence on maize production for Bako under the future climate. For lower altitudes, late planting would have lower relative yields compared to early planting. Higher fertilizer levels (100–150 kg ha^{-1}) would reduce yield reductions under the future climate, but this varied among maize cultivars studied. Generally, the future climate is expected to have a negative impact on maize yield and changes in crop management practices can alleviate the impacts on yield.

Keywords: adaptation options; crop models; GCMs; multimodel ensemble; representative concentration pathway

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1. Introduction

Climate change has become a major environmental and socio-economic threat to the world. Past climate change studies in Ethiopia have shown significant changes in air temperature [1,2] and precipitation patterns [3–5] in the past decades. Climate change projection studies based on emission scenarios indicate air temperature increases over the country [6] by the year 2050. Similarly, by 2050 mean annual rainfall is expected to increase by 1%, with high uncertainty, in amount and intensity [7]. Climate change influences agriculture by affecting the crop's physiological processes. The change in the amount and distribution of precipitation and air temperature affect crop water balance by modifying evapotranspiration which in turn affects yields [8].

Agriculture is a fundamental part of the economy in Ethiopia. With a population of more than 110 million [9], Ethiopia is the second most highly populous country in Africa. Over 70% of the population is engaged in subsistence farming [10]. Agriculture accounts for almost one-third of the change in Gross Value Added per capita as compared to the industrial sector, which contributed about 22.2%. Agriculture in Ethiopia is the basis of the economy, contributing 35.8% of the GDP [10]. However, agriculture in Ethiopia is highly affected by rainfall variability and recurrent drought, resulting in severe food insecurity [11]. Moreover, climate change seriously impacts agricultural productivity and causes the loss of human life and livestock [12]. According to [13], the frequency of drought and irregular precipitation occurrences has increased in recent decades and continues to increase with increased impacts under future climate change [14,15]. There is no doubt that Ethiopia's agriculture is already extremely vulnerable to climate change and consequential crop failure [11]. It is thus very important to assess the impacts of future climate for proper adaptation mechanisms [7,16].

Maize (*Zea mays* L.) is one of the dominant cereal food crops second after tef (*Eragrostis tef*) in terms of production and area coverage in Ethiopia. In the 2019/2020 production season, 2.3 million hectares of land were under maize cultivation at the national level from which 9.6 million tons of yield was produced by more than 11.4 million smallholder farmers [17]. About 88% of maize production in the country is consumed as food, both as green and dry grain [18]. However, the production of maize is seriously limited due to abiotic and biotic factors, such as drought, low soil fertility, insufficient improved varieties, pests, and diseases [19–21]. In addition, maize yield reduction in Ethiopia is exacerbated by climate change [22]. Recent climate projections indicate that in the near (2035) and mid-future (2055), there will be an increase in air temperature in most parts of Ethiopia resulting in an average decrease in maize yield for the coming years [23].

Adaptation is a key factor in agriculture to reduce the impacts of climate change [24–26]. Authors of Ref. [23] emphasized that alternative agronomic practices, such as fertilizer use, shifting planting dates, and change in cultivars, are possible solutions to the negative impacts of climate change with improvements to maize production in Ethiopia. Studies also revealed that adaptation options should be site-specific and need to be addressed for the various agroecological zones [27,28].

Process-based crop simulation models (hereafter referred to as crop models) are commonly applied tools for multiple areas to assess the impact of climate variability and change on agricultural production [29–34]. The coupling of crop models to climate models has been a common method for analyzing the potential impact of climate change on crop production and evaluating adaptation options [35].

In Ethiopia, various climate change impact assessment studies have been conducted using crop models to simulate maize yield under different environments and field conditions [21–23,36–39]. The purpose of most of these studies was limited to climate change impacts, yield variability, and yield gap estimation of maize and did not consider the adaptation aspect. Only a few studies addressed both climate change impacts and adaptation options on maize productivity in Ethiopia, such as [37–39]. Nevertheless, both studies used one or two crop model(s) to simulate maize yield which is still inadequate for a detailed analysis of crop model uncertainty. Authors of Ref. [21] also recommended the multi-crop model approach and multi-GCM ensemble projections for more in-depth analysis and reliable climate change sensitive assessments. In addition, there is insufficient research devoted to adaptation strategies developed based on climate change scenarios in Ethiopia [40]. Hence, there is a need to design climate change adaptation strategies using multiple crops and climate models under the future climate.

Therefore, the objectives of this study were to (1) assess the impact of climate change on maize yield, and (2) identify possible adaptation mechanisms using multiple crop models and multiple climate models at three sites representing contrasting agroecological zones in Ethiopia.

2. Materials and Methods

2.1. The Study Sites

The sites used in this study are located in central Ethiopia (Ambo, high altitude), south-western Ethiopia (Bako, mid-altitude), and central Rift Valley of Ethiopia (Melkassa, low altitude). They have different soil and climatic characteristics and hence maize cultivars that differ in their maturity period are grown across the study sites. The soils range from sandy clay loam to clay texture. The seasonal rainfall and reference evapotranspiration ranged from 587 to 1206 mm and 431 to 770 mm, respectively. The mean maximum and minimum air temperature ranges from 24.0 to 28.4 °C and 10.3 to 14.5 °C during the maize growing season in the study sites (Table 1). Maize field experiments were conducted under rainfed conditions for the sites. Detailed information can be found in [40].

Table 1. Characteristics of the study sites in Ethiopia.

Location	Ambo	Bako	Melkassa
Latitude (°)	8.57	9.12	8.42
Longitude (°)	38.07	37.04	39.32
Altitude (m)	2225	1650	1550
Soil characteristics			
Soil type	Eutric regoSol	Nitosol	Vitric andosols
Soil texture	sandy clay loam	clay	loam
Baseline climate (1995–2017)			
Seasonal total precipitation (mm)	718	1206	587
Seasonal ET_o (mm) *	543	431	770
Mean max. air temperature (°C)	24.0	24.0	28.4
Mean min. air temperature (°C)	10.3	14.5	13.9

* ET_o: grass reference evapotranspiration.

2.2. Data Collection

2.2.1. Weather, Soil, and Crop Data

Historical weather and soil data are the main input data sources used in the crop models, in addition to crop management practices such as planting date, plant density, row spacing, and fertilization. For Ambo, Bako, and Melkassa the daily rainfall, maximum and minimum air temperature, and solar radiation data for the study sites were obtained from meteorological stations at the experimental sites and/or from the national meteorological agency where the study sites are located (for the spatial location map, ref. [41]). Daily grass reference evapotranspiration (ETo) was computed by the FAO Penman-Monteith method [42,43]. For the weather data quality control measures were undertaken and patching of missing values was utilized using [42] for all the study sites. The soil profile data were obtained from [44,45] and the International Maize and Wheat Improvement Center (CIMMYT) in Ethiopia and field measurements.

Four improved and most widely grown hybrid maize cultivars were used for this study. The hybrid maize cultivars were Jibat, BH661, BH546, and MH140. The choice of maize cultivars was based on farmers' preferences.

2.2.2. Crop Simulation Models

Maize yield was simulated using three crop simulation models, namely Agricultural Production Systems Simulator (APSIM)-maize v 7.9 [46], FAO—AquaCrop v. 7.9 [47], and Decision Support System for Agrotechnology Transfer (DSSAT)—CERES—maize v 4.7 [48] (hereafter, the crop models are referred to as APSIM, AquaCrop and DSSAT respectively). These crop models have been used widely and provide a realistic simulation of maize yield across the world [49–51] under both current and future climate change conditions. The input data to run the models are daily total solar radiation (calculated from daily sunshine hours data), daily minimum and maximum air temperatures, and daily precipitation. Additional inputs necessary to run the crop models are soil type, cultivar type, and crop management. This study is based on well-calibrated and evaluated crop models in our previously published article [41]. The three crop models were calibrated and evaluated for four maize cultivars (Jibat, BH661, BH546, and MH140) using data from field trials conducted in the 2017/18 cropping season in Ethiopia [41]. For a detail description of the individual models and their calibration and evaluation, refer to [41].

2.2.3. Climate Change Projections

The daily climate data downscaled from seven Global Circulation Models (GCMs), namely, CanESM2, CNRM-CM5, CSIRO-MK3-6-0, EC-EARTH, HadGEM2-ES, IPSL-CM5A-MR, and MIROC5 from the Coupled Model Intercomparison project phase 5 (CMIP5) were used to simulate maize yield in this study. The GCMs used in this study are listed in Table 2 together with the institutions which developed them, their country of origin, and references.

Table 2. Description of the global climate models (GCMs) used.

GCM Name	Institute	Country	References
CanESM2	CCCma: Canadian Centre for Climate Modelling and Analysis	Canada	[52]
CNRM-CM5	CERFACS: Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique	France	[53]
CSIRO-MK3-6-0	CSIRO: Commonwealth Scientific and Industrial Research Organization	Australia	[54]
EC-EARTH	ICHEC: Consortium of European research institutions and researchers	Europe	[55]
HadGEM2-ES	MOHC: Met Office Hadley Centre	United Kingdom	[56]
IPSL-CM5A-MR	IPSL: Institut Pierre Simon Laplace	France	[57]
MIROC5	AORI: Atmospheric and Ocean Research Institute	Japan	[58]

The data were downscaled using the Regional Climate Model (RCM)-RCA4 [59]. The RCM-RCA4 simulation covers the Coordinated Regional Climate Downscaling Experiment (CORDEX)-Africa domain at a 44-km horizontal resolution in Africa for the 1951–2100 periods which is divided into two: historical (1951–2005) and scenario (2006–2100) periods. The CORDEX initiative sets a standard grid, domain size experiment protocols, and data format allowing for direct comparison of the model outputs [60,61]. Within this framework, only models which were widely available and provide projections for the Representative Concentration Pathway (RCP 8.5) were selected as this is deemed the highest level expected to assess future climate change impact and responses. There is no difference between RCP 4.5 and RCP 8.5 until the year 2050 [62,63]. The difference between the two becomes clear after 2050. Therefore, all projected climate and crop model simulations in our study are based on RCP 8.5 emission scenario.

The data were bias-corrected using the quantile-quantile mapping procedure [64]. Atmospheric CO_2 concentrations specified for each period according to the Intergovernmental Panel on Climate Change Special Report on Emission Scenarios IPCC SRES [40] were used: 380 $\mu L\ L^{-1}$ for the baseline (1995–2017) and 450 $\mu L\ L^{-1}$ for the future (2021–2050) period. In this study, downscaled precipitation, and maximum and minimum air temperature data from seven GCMs for the three study sites (Ambo, Bako, and Melkassa) were evaluated. The baseline data at a daily scale (1995–2017) were used for evaluating CORDEX-Africa precipitation, and maximum and minimum air temperature for future climate scenarios. The comparison between GCM's historical runs and observations was performed using average monthly values of precipitation, and maximum and minimum air temperature for the reference period of 1995–2005. The performance of GCMs in simulating the observed precipitation, and maximum and minimum air temperature data were evaluated statistically and presented graphically. The statistical measurements include root mean square error (RMSE) and correlation coefficient (R^2) calculated using the following equations:

$$R^2 = \frac{n * \sqrt{\sum Si \times Oi} - \sum Si \times \sum Oi}{\sqrt{[n * \sum Si^2 - (\sum Si)^2] * [[n * \sum Oi^2 - (\sum SOi)^2]}} \quad (1)$$

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (Si - Oi)^2} \quad (2)$$

where Si and Oi represent the simulated and the observed values of the ith year respectively, and n is the total number of years that data values were used.

2.2.4. Crop Management Practices for Climate Change Adaptation

The study considered three agronomic management options: planting date shift, nitrogen fertilizer levels, and maize cultivars with different maturity lengths. To assess the impact of climate change on maize yield, the study considered the recommended planting date, nitrogen fertilizer level, and cultivar for each site studied as a control treatment for the baseline period. The control treatments are planting dates: 15 June for Ambo and Bako and 30 June for Melkassa. Nitrogen fertilizer: 100 kg ha^{-1} used for all sites. Maize cultivars: late maturing (Jibat) for Ambo, late (BH661) and medium (BH546) maturing for Bako, and early maturing (MH140) for Melkassa. These treatments are the baseline practices used by farmers and agricultural research centers in the respective study sites. The control treatments were simulated for the baseline (1995–2017) and for the future 2021–2050 (the 2030s) climate. The relative yield reduction was used as a measure of climate change impact. To assess the adaptation options for the baseline and for the future period, shifting the planting date within the planting window (15 May to 15 July) was used. The normal planting periods were between 15 May to 15 June for Ambo and Bako, and between 1 June to 15 July for Melkassa [65].

Optimum planting dates, which provided the highest yield, were determined from simulations of the baseline and the climate change scenarios using sowing dates of two weeks intervals around the earliest and latest possible sowing date within the planting window. Hence, we adopted four different planting dates: 15 May, 1 June, 15 June, and 30 June for Ambo and Bako, and 1 June, 15 June, 30 June, and 15 July for Melkassa. Different nitrogen fertilizer levels below and above the recommended level (0, 23, 100, 150, and 200 kg ha^{-1}) were used with 50% nitrogen at planting and 50% of nitrogen 30 days after planting. Four different maize cultivars: BH546, BH661, Jibat, and MH140 under three maize agro-ecology zones were also used as future adaptation options. Maize yield was simulated for a baseline period (1995–2017) and future 2021–2050 (the 2030s) climatic conditions. The 2030s represent the average between 2021 and 2050. The potential impact of climate change under the RCP8.5 scenario was estimated by calculating changes in maize yield between baseline and future climates for each treatment as follows:

$$\Delta Y = \frac{\left(Y_{fi} - Y_b\right)}{Y_b} \quad (3)$$

where ΔY is a change of yield, Y_{fi} is yield under future climate i, and Y_b is yield under the baseline climate.

The variability of yield (uncertainty) due to temporal variation, model, or location in the climate change impact assessment was calculated based on the method described in [66]. Note that ensemble GCMs refer to the results averaged over the seven GCMs while ensemble crop models refer to the results averaged over the three crop models.

3. Results

3.1. Projected Climate Change by 2030s

3.1.1. Precipitation

Projections using RCP 8.5 at Ambo, Bako, and Melkassa sites clearly showed changes in monthly precipitation amount by 2030. Relative to the baseline period (1995–2017), the percentage changes in monthly total precipitation by 2030 varied among GCMs and sites (Supplementary Figure S1). The monthly total precipitation for the most relevant months from the point of view of rainfed crop production (i.e., June to September- Kiremt season) is projected to increase by up to 55% (365 mm) for Ambo and 75% (241 mm) for Bako respectively, whereas a significant decrease in monthly total precipitation is projected for Melkassa compared to the baseline period by 2030 (Supplementary Figure S1). For the short rainy season (March to May-Belg season), most of the GCMs projected a decrease in monthly total precipitation for all sites, except a few GCM models that projected a slight increase for Bako relative to the baseline period. Interestingly, the total monthly precipitation for the dry season (October to February-Bega season) for almost all GCM models projected a great increase for Melkassa particularly for November, December, and January. Similarly, most of the GCMs projected an increase in monthly total precipitation for October and November in Ambo while the majority of the GCM models projected a decrease in monthly total precipitation for Bako in the near future (the 2030s) (Supplementary Figure S1).

Figure 1 shows the total monthly precipitation amount projected by an ensemble of multiple GCMs for 2030 as compared to the observed (1995–2017) period. Results show that monthly total precipitation will remain almost the same as the baseline, while the in Belg (Mar–May) season total precipitation will decrease at Ambo under the future climate. In the Kiremt (Jun–Sept) season, monthly total precipitation, on the other hand, may significantly increase at Bako in 2030. However, future monthly total precipitation is projected to reduce significantly for Belg and Kiremt seasons at Melkassa by 2030 (Figure 1).

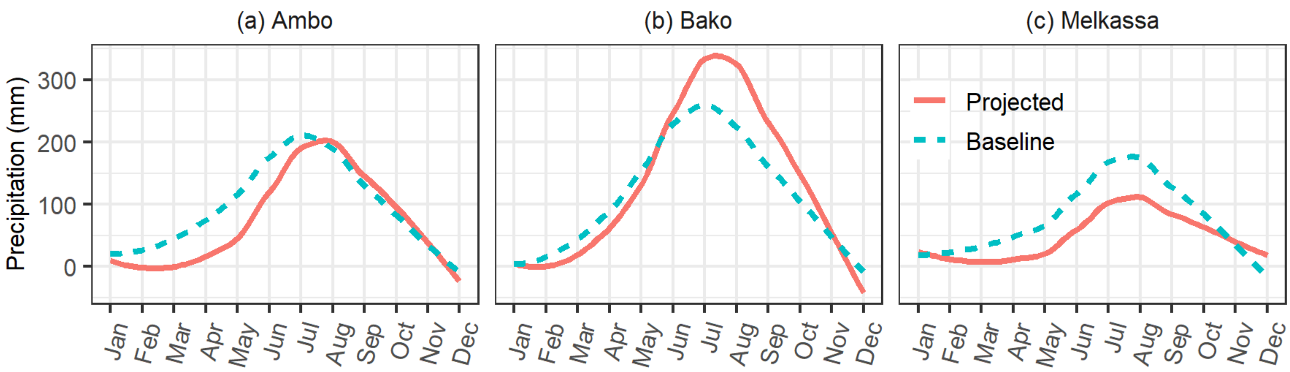


Figure 1. Total monthly precipitation amount projected by the multimodel ensemble for 2030 compared to that observed (1995–2017) period for (**a**) Ambo (high altitude), (**b**) Bako (mid-altitude), and (**c**) Melkassa (low altitude).

3.1.2. Maximum Air Temperature

The projected changes in average monthly maximum air temperatures from all GCM runs are shown in Supplementary Figure S2. The changes in average monthly maximum air temperatures projected by GCMs are quite different in magnitude, but similar in pattern. All models indicate incremental changes with respect to the historical period in the near future. According to the GCM models, the average monthly maximum air temperatures would increase by 0.3–1.7 °C for Ambo, 0.7–2.2 °C for Bako, and 0.8–1.8 °C for Melkassa compared to the historical period (Supplementary Figure S2). In addition, the Kiremt season will experience the highest air temperature change, particularly in the month of August at Ambo. Similarly, the Bega season will experience the highest air temperature in February and January at Bako and Melkassa respectively in 2030. Overall, for a given future period and emission scenario though, warming is found for all study sites although larger relative increases are projected for Bako.

Monthly average maximum air temperature projected values obtained by the GCMs ensemble, and the observed values are presented in Figure 2. According to the GCMs ensemble means, the monthly average maximum air temperature is expected to increase by 24.0–29.7, 25.6–33.1, and 27.8–32.5 °C for Ambo, Bako, and Melkassa respectively compared to that observed by 2030. In addition, the GCMs ensemble means clearly indicate that the increase in monthly average maximum air temperature by the 2030 will be higher during the small rainy season (Belg) and the dry season (Bega) across all sites compared to the main rainy season (Kiremt) (Figure 2).

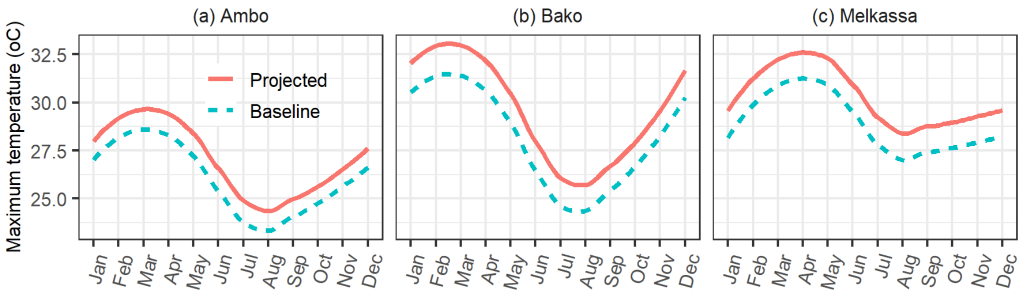


Figure 2. Multimodel ensemble average monthly maximum air temperature projected for 2030 compared to that observed (1995–2017) period for (**a**) Ambo (high altitude), (**b**) Bako (mid-altitude), and (**c**) Melkassa (low altitude).

3.1.3. Minimum Air Temperature

The results of projections for monthly average minimum air temperature are shown in Supplementary Figure S3. The projection shows that the monthly average minimum air temperatures are projected to continue to increase in comparison to the historical period. Likewise, the monthly average minimum air temperature is projected to increase in the range of 0.6–1.7 °C for Ambo, 0.8–2.3 °C for Bako, and 0.6–2.7 °C for Melkassa in 2030 (Supplementary Figure S3). This is greater than the 2 °C limit specified by the IPCC as the point beyond which ecological systems may become severely disrupted [40]. The result also clearly shows that the future average monthly minimum air temperature increases are similar to the results shown for average monthly maximum air temperature changes. In addition, the Kiremt season will experience the highest monthly average minimum air temperatures in June at Ambo in the near future. Similarly, the Bega season will have the greatest monthly average minimum air temperature in December and October at Bako and Melkassa respectively in 2030. Overall, for the period of 2030, there will be a clear increase in the average monthly minimum air temperature compared to the maximum air temperature change, due to climate change impacts.

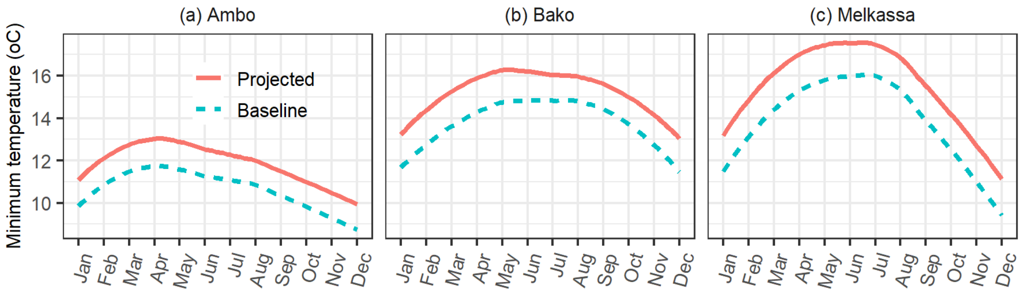


Figure 3. Multimodel ensemble average monthly minimum air temperature projected for 2030 compared to that observed (1995–2017) period for (**a**) Ambo (high altitude), (**b**) Bako (mid-altitude), and (**c**) Melkassa (low altitude).

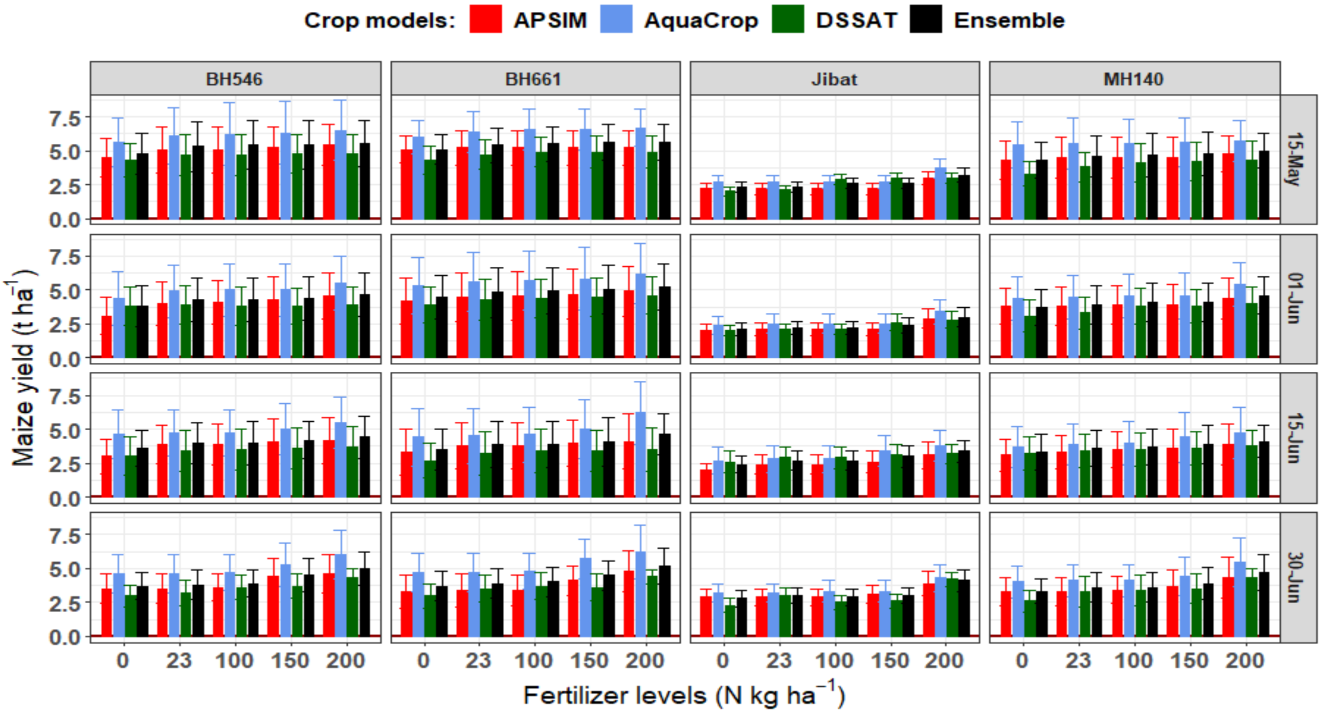
The projected values of the monthly average minimum air temperature obtained by the GCM ensembles and the observed values are presented in Figure 3. The ensemble GCMs were able to replicate the monthly average downward trend in minimum air temperature levels as the observed data show (Figure 3). Based on the GCMs ensemble projections, the monthly average minimum air temperature is expected to increase by 10.1–13.2, 13.2–16.5, and 11.6–18.0 °C for Ambo, Bako, and Melkassa respectively compared to that observed in the near future. According to the GCMs ensemble means, by 2030 the increase in monthly average minimum air temperature will be higher during the Belg (Mar–May) season for all sites studied as compared to the other two seasons (Figure 3).

3.2. Yield Simulation for the Baseline (1995–2017) Climate

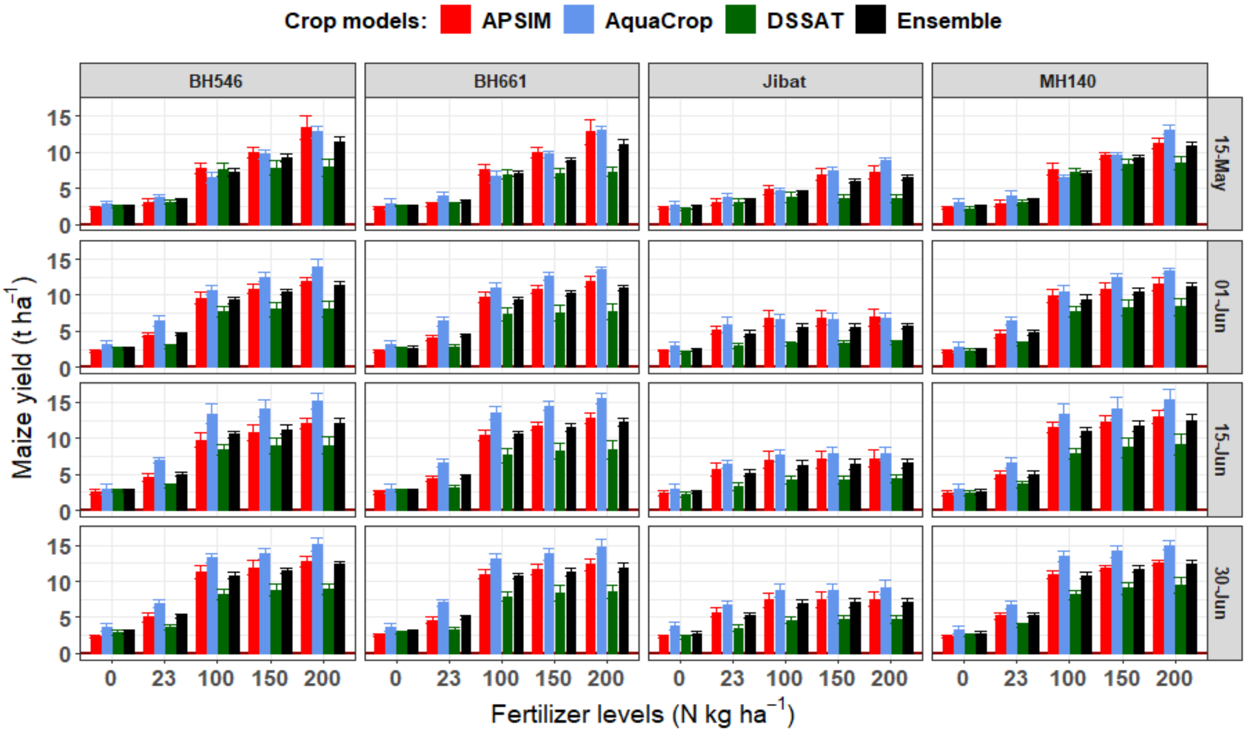
Yield simulations for the baseline period using the observed climate data indicated higher yields at mid-altitude yields for Bako (Figure 4). Simulation of yield by all crop models suggests that increased nitrogen (N) application produces an increased yield for all maize cultivars on all sites. The simulated maize yield for Ambo ranges between 2.0 and 6.7 t ha^{-1}, 2.0 and 15.5 t ha^{-1} for Bako, and 2.9 and 13.1 t ha^{-1} for Melkassa for the baseline 1995–2017 period. The average of the three models provides an increased yield (up to 12.5 t ha^{-1}) as compared to the measured maize yield values (up to 6.7 t ha^{-1}) across all cultivars and sites.

3.3. Impact of Projected Climate on Maize Yield

Figure 5 presents the impact of future climate on maize yield if the existing agronomic practices used by farmers continue in 2030 in the study sites. Relative to the baseline, all the crop models showed either an increase or a decrease in maize yield depending on the treatment level. Figure 5 Assuming the current agronomic practice in the future climate, the mean (i.e., averaged over all cultivars and crop models and climate models) maize yield is expected to decrease by 4 % and 16 % for Ambo and Melkassa, respectively, by 2030 (Figure 5). In contrast, the corresponding mean maize yield is expected to increase by 2% for Bako by 2030 (Figure 5). Note that, the current planting dates are 15 June for Ambo and Bako, and 30 June for Melkassa whereas the control Nitrogen fertilizer was 100 kg ha^{-1} for all sites to reflect the “no adaptation option”.

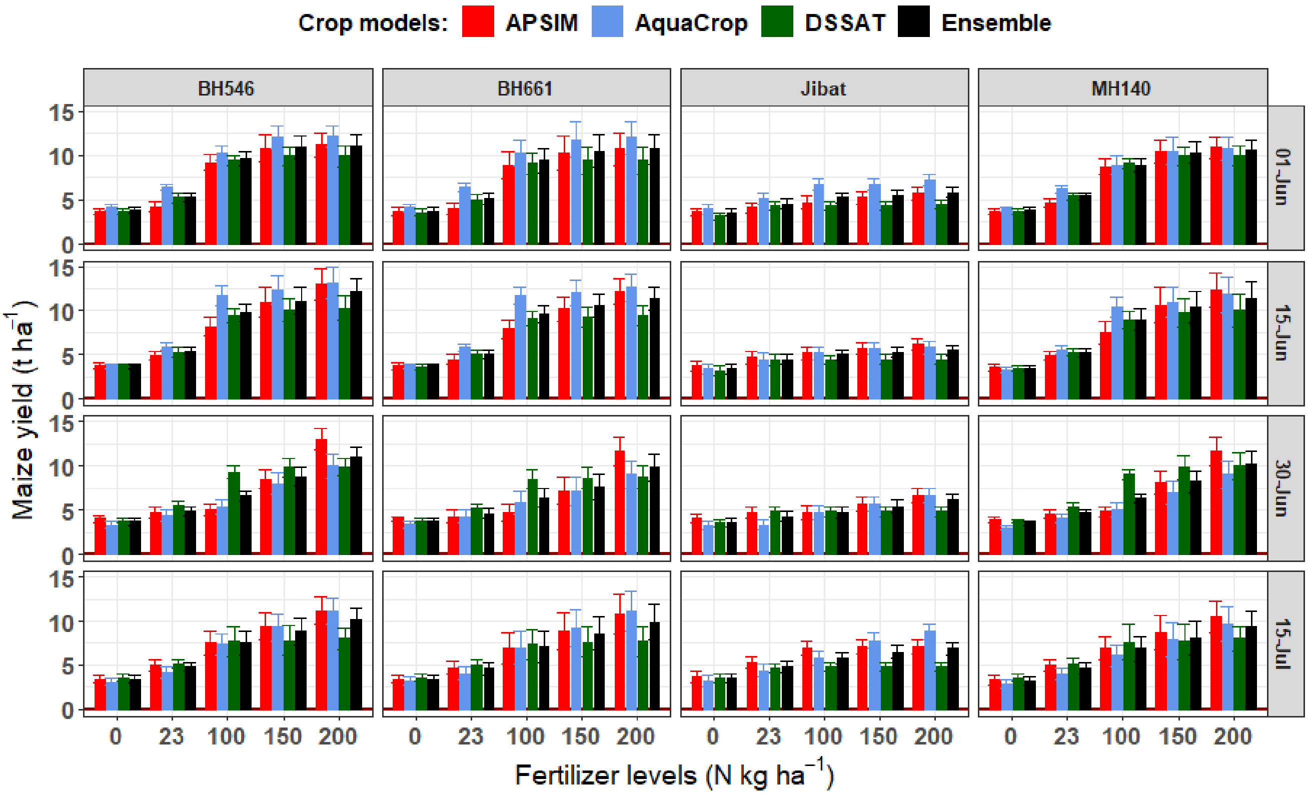


(**a**) Ambo



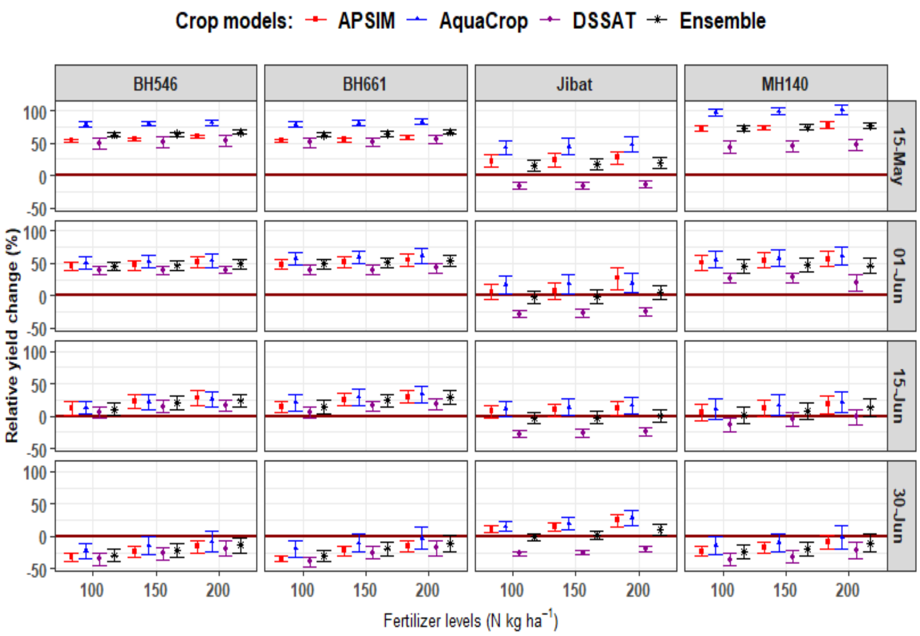
(**b**) Bako

Figure 4. *Cont.*

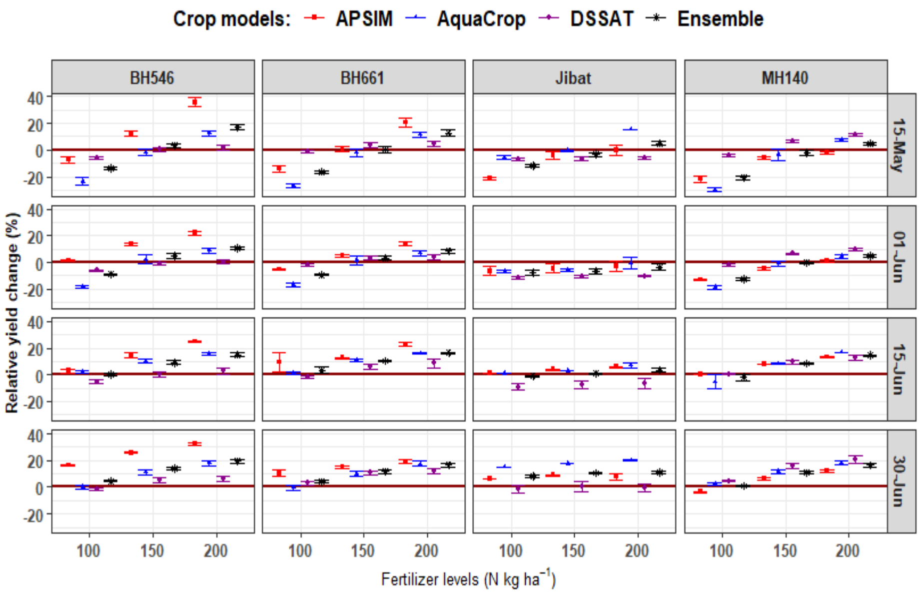


(**c**) Melkassa

Figure 4. Maize yield (t ha^{-1}) with observed climate data for the baseline period (1995–2017) as simulated with APSIM, AquaCrop, and DSSAT models using different planting dates, cultivars, and nitrogen fertilizer levels for (**a**) Ambo (high altitude), (**b**) Bako (mid-altitude), and (**c**) Melkassa (low altitude). Error bars show the standard deviation of maize yield simulated by the crop models.

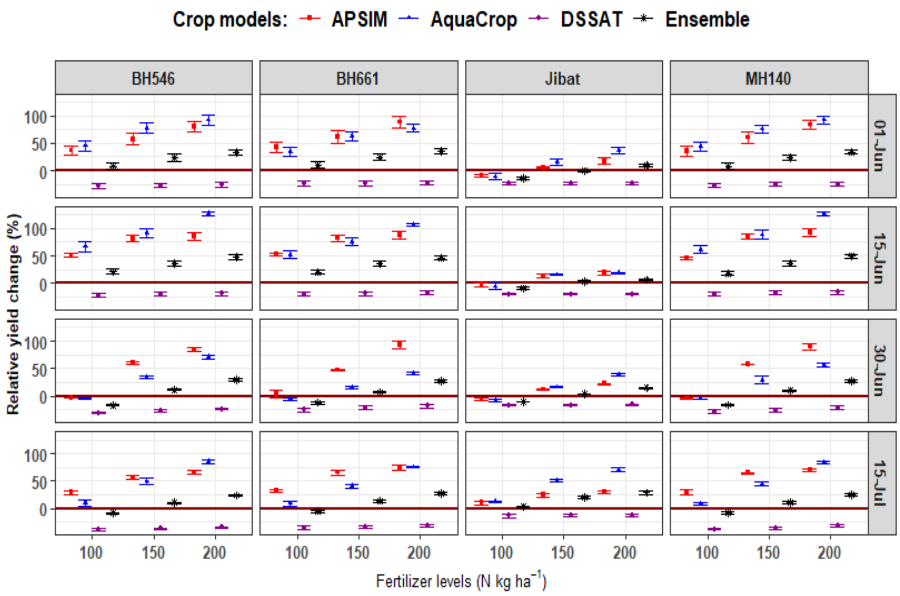


(**a**) Ambo



(**b**) Bako

Figure 5. *Cont.*



(**c**) Melkassa

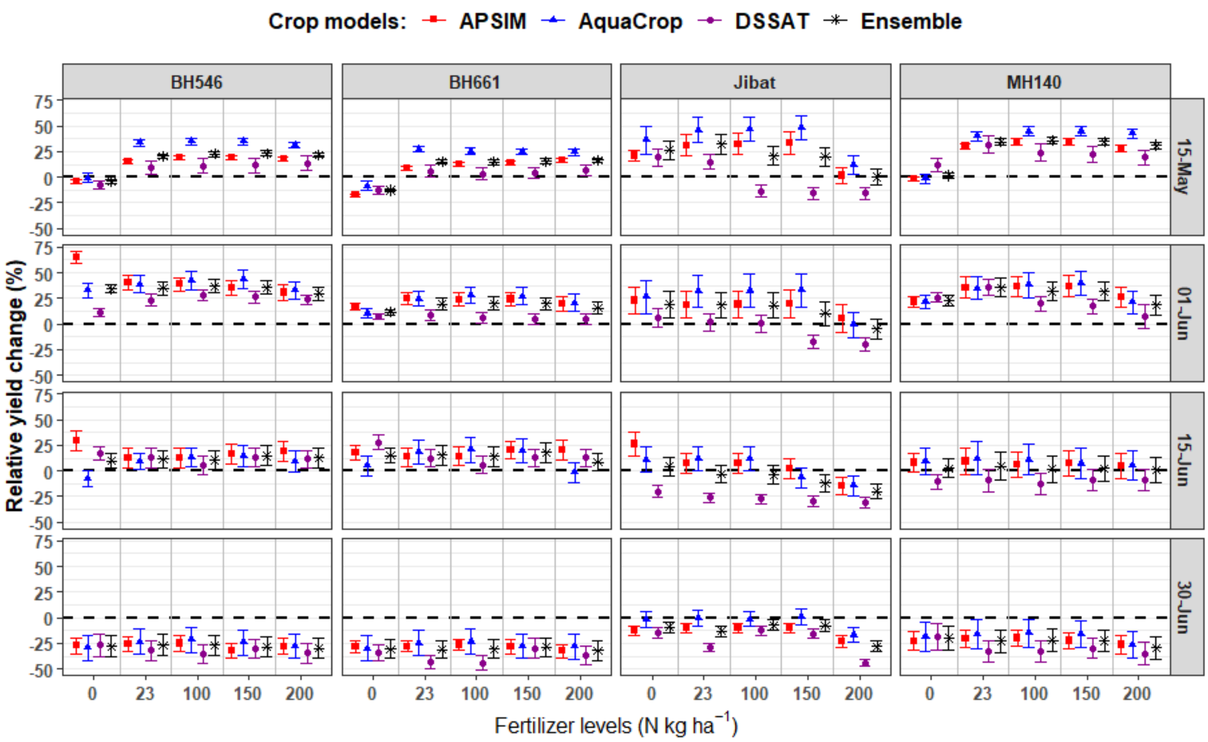
Figure 5. Percentage yield change in 2030 relative to the baseline control treatments as simulated with APSIM, AquaCrop, and DSSAT crop models for (**a**) Ambo (high altitude), (**b**) Bako (mid-altitude), and (**c**) Melkassa (low altitude). Error bars show the standard deviation of the change of maize yield simulated for multiple GCM projections.

3.4. Crop Management Practices as Adaptation Options

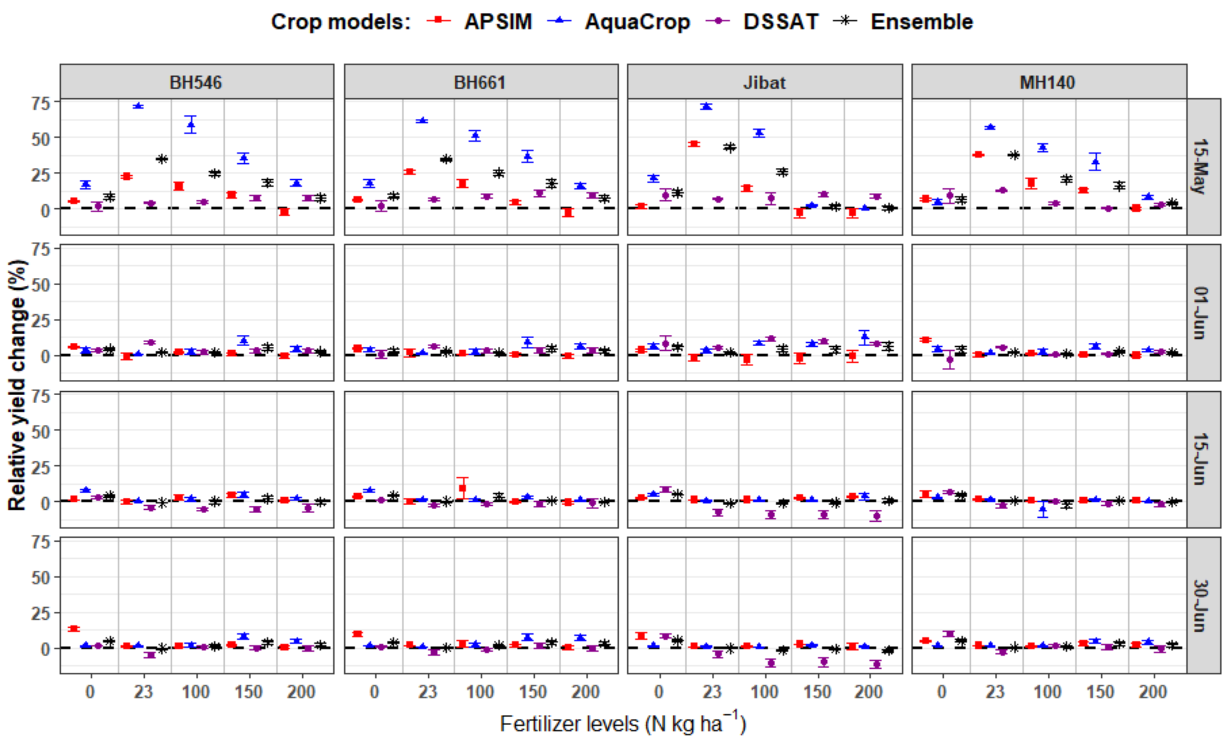
According to Figure 6, the result indicated that for Ambo crop model differences in predicting maize yield are small. Early planting from 15 May to 1 June would give improved relative yields for all cultivars. Fertilizer levels increment between 23–150 kg ha^{-1} result in progressive yield improvement for all cultivars when combined with early planting at Ambo in 2030.

For Bako, there are differences between the models in the relative yield changes of maize, particularly for the early planting dates. Early planting increased maize yield for all cultivars under the future climate. Planting after 15 May has either no effect or has a negative effect on maize yield. All cultivars studied responded in the same way to planting date shifts. Early planting combined with a nitrogen fertilizer level of 23–100 kg ha^{-1} provided increased relative yields under the future climate. Delayed planting has a negative influence on maize production for Bako under the future climate (2030).

For Melkassa, all models responded similarly to planting dates, fertilizer, and cultivar levels. All planting dates considered resulted in negative relative yield. However, late planting had reduced relative yields compared to early planting. Higher fertilizer levels (100–150 kg ha^{-1}) seem to reduce yield reductions under the future climate, but this varied among maize cultivars studied. Planting the Jibat cultivar between 15 and 30 June at higher N levels may reduce severe yield reduction of maize at Melkassa (Figure 6).

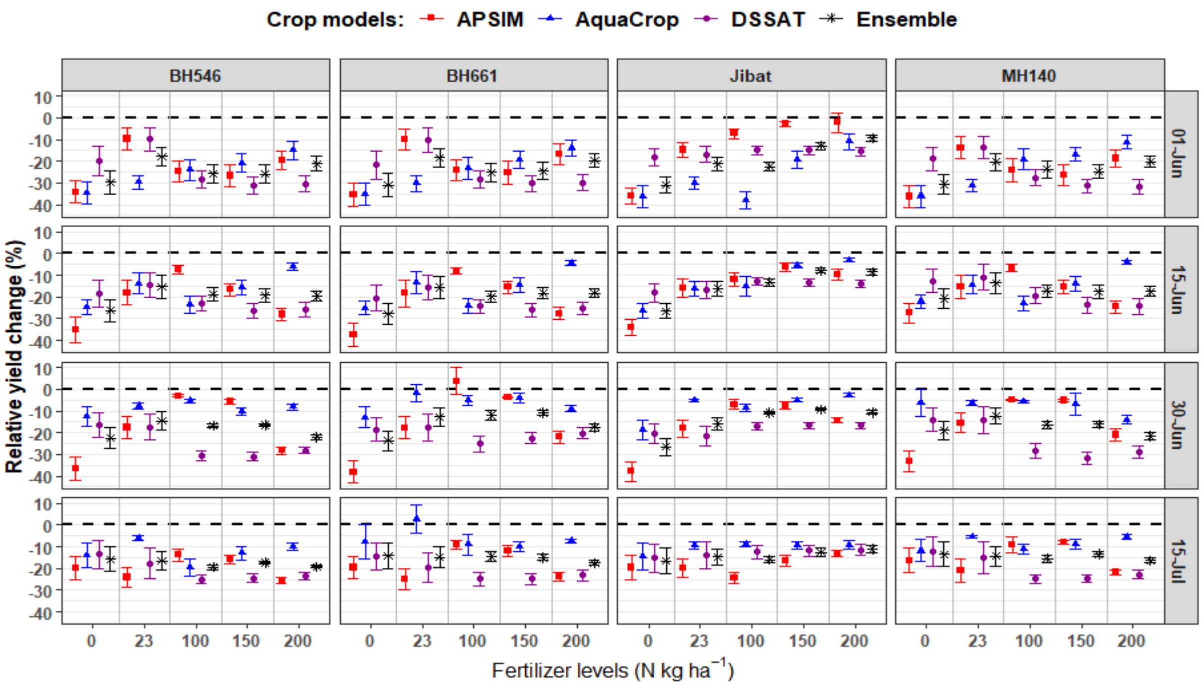


(**a**) Ambo



(**b**) Bako

Figure 6. *Cont.*

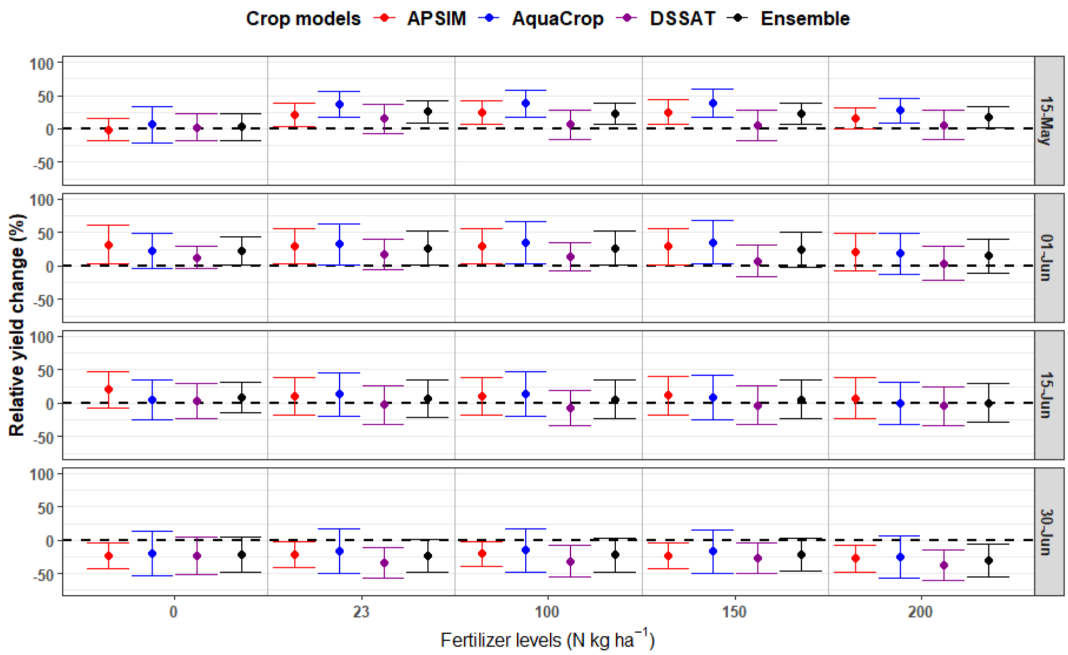


(**c**) Melkassa

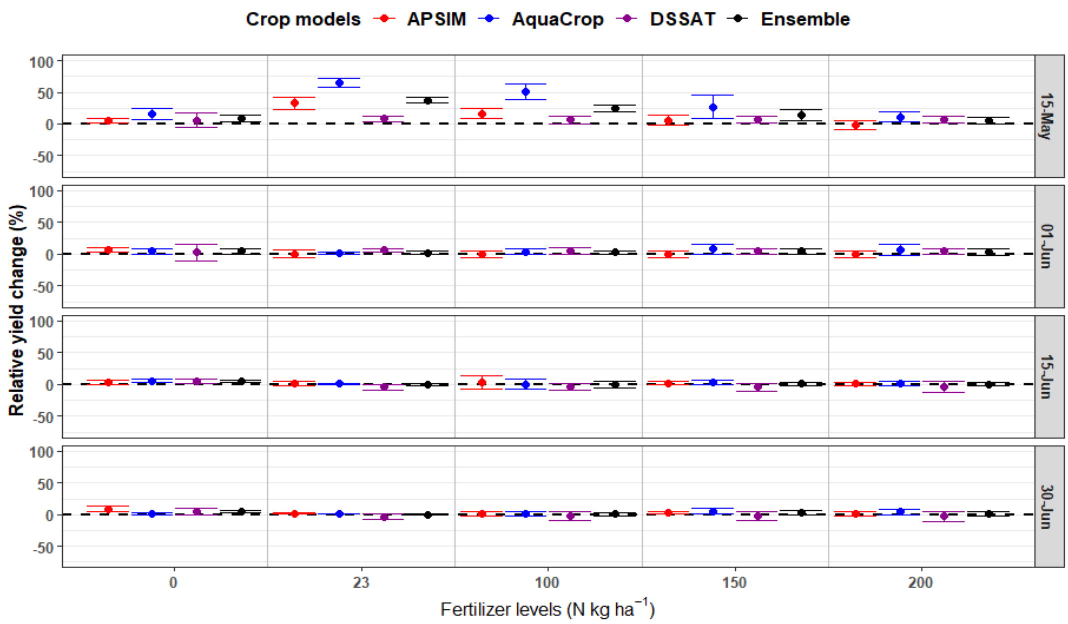
Figure 6. Effects of planting dates on mean maize yield under future climate change scenarios relative to the baseline for (**a**) Ambo (high altitude), (**b**) Bako (mid-altitude), and (**c**) Melkassa (low altitude) as simulated using the APSIM, AquaCrop, and DSSAT crop models. Error bars show the standard deviation of the change of maize yield simulated for multiple GCM projections.

3.5. Crop Model Uncertainty in Yield Simulation

Predicted yield differences amongst the models were noted for the higher altitude (Ambo), mid (Bako), and lower altitude (Melkassa) sites. The impact of the crop models in predicting yield varied from −38 to 38% for Ambo, from −4 to 65% for Bako, and −12 to −36% for Melkassa (Figure 7). The crop model yields were inconsistent even for the simulated mean yield change under the same climate projection. The DSSAT model projected a large mean yield reduction whereas the AquaCrop model projected a high mean yield increase for Ambo and Bako for most climate projections. The APSIM model projected both the lowest and the highest yield reduction for Melkassa for most of the climate projections (Figure 7). The differences in the simulated mean yield changes could to some extent be attributed to the different responses of these crop models to the projected climate conditions.

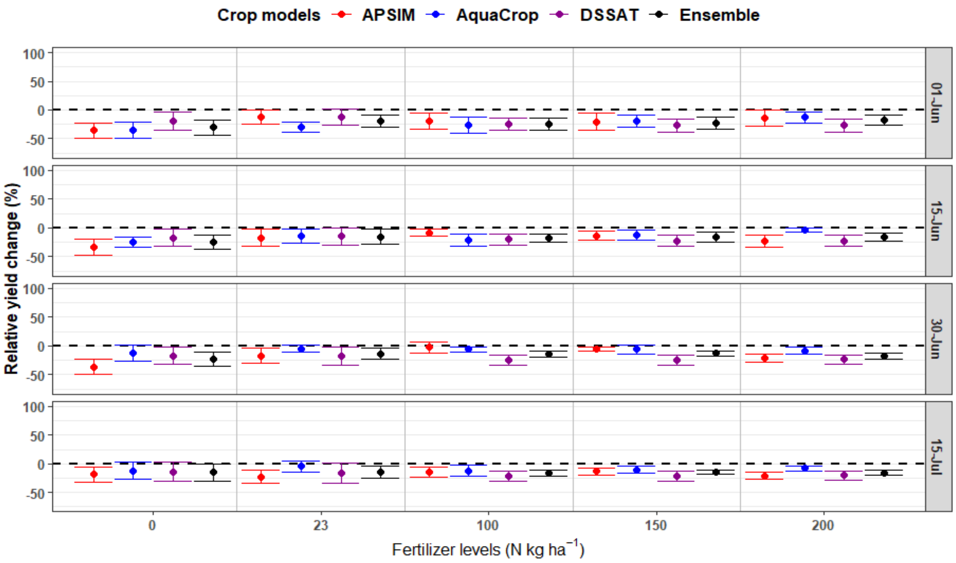


(**a**) Ambo



(**b**) Bako

Figure 7. *Cont.*

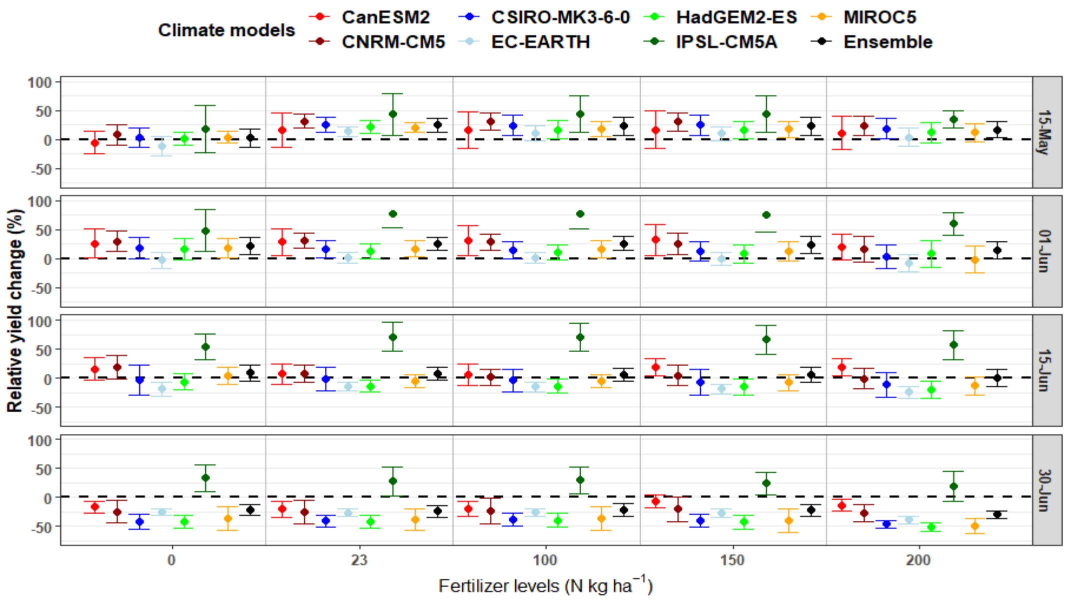


(**c**) Melkassa

Figure 7. Crop model uncertainty in simulated mean maize yield (averaged for all cultivars) for different planting dates and nitrogen fertilizer levels for (**a**) Ambo (high-altitude), (**b**) Bako (mid-altitude), and (**c**) Melkassa (low-altitude). Error bars show the standard deviation of the change in maize yield simulated by the individual GCM projections.

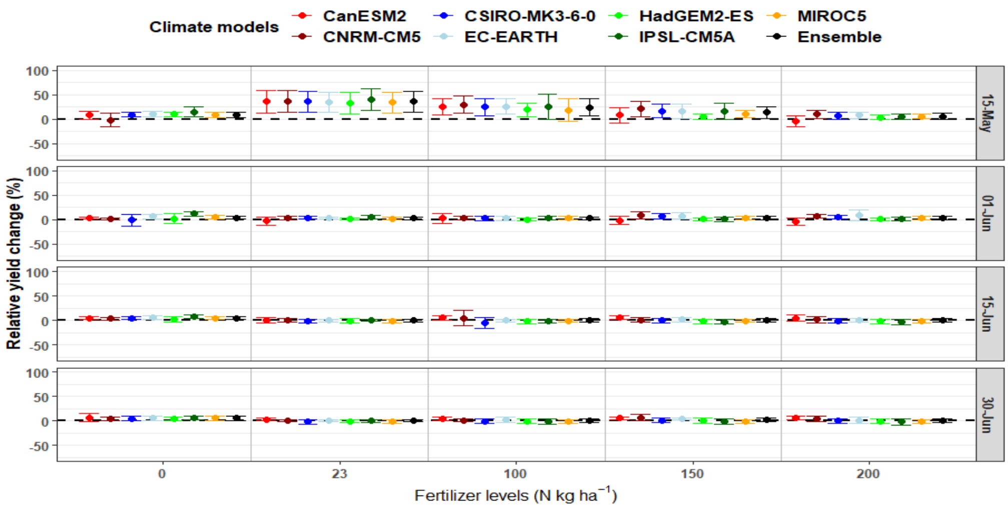
3.6. Climate Model Uncertainty in Yield Simulation

The simulated mean maize yield changes for different climate projections were quite different. For example, using the IPSL-CM5A resulted in the highest mean yield increase for both Ambo and Bako, whereas data for HadGEM2-ES and CSIRO-Mk3-6-0 models resulted in the lowest mean yield for Ambo and Bako respectively. Both the HadGEM2-ES and CSIRO-Mk3-6-0 models projected the lowest and the highest decrease in mean yield, respectively for Melkassa (Figure 8). Overall, the impact of the choice of GCM on yield varied from −52 to 78% for Ambo, −5 to 41% for Bako, and −4 to −62% for Melkassa (Figure 8). This result demonstrated that the yield uncertainty is greater among GCMs than crop models.

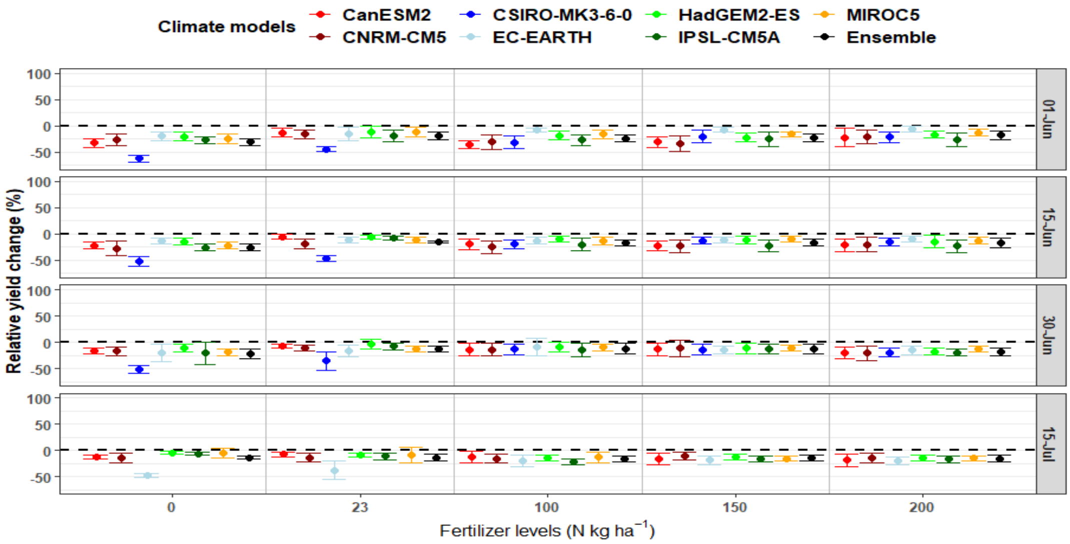


(**a**) Ambo

Figure 8. *Cont.*



(**b**) Bako



(**c**) Melkassa

Figure 8. Climate model uncertainty in simulated mean maize yield (averaged for all cultivars) for different planting dates and nitrogen fertilizer levels for (**a**) Ambo (high altitude), (**b**) Bako (mid-altitude), and (**c**) Melkassa (low altitude). Error bars show the standard deviation of projected maize yield changes across the three crop models.

4. Discussion

4.1. Climate Change Projections and Impacts

Maize production is very likely to be negatively affected by climate change in Ethiopia [37,38] and there is an urgent need to develop strategies that adapt to the changing climate. Therefore, this study investigated the potential impact of climate change on maize yield for three sites (Ambo, Bako, and Melkassa) in tropical environments of Ethiopia in 2030 under RCP 8.5 scenario using downscaled CORDEX-Africa domain precipitation and air temperature data. The study indicated that both the individual GCM models and their ensemble mean projected an increase for the Kiremt season total monthly precipitation for Ambo and Bako while a decrease in total monthly precipitation for Melkassa by 2030 as compared to the baseline period. A projected precipitation increase for the Kiremt season up to 55% (365 mm) for Ambo and 75% (241 mm) for Bako, respectively, can be explained since the two sites received more precipitation as compared to the low-land areas, such as Melkassa (Figure 1). Moreover, the Kiremt season is the main rainy season which receives most of the annual precipitation. Hence, the future climate might favor the site during this season. A future increase in the Kiremt total monthly precipitation at Ambo and Bako may have a positive impact on maize production though this might be changed due to an increase in the air temperature for the sites that leads to an increase in evapotranspiration [7].

The result from the GCMs model showed that the Belg season total monthly precipitation was projected to decrease for Ambo and Melkassa while projected to increase for Bako by 2030. However, the GCMs ensemble clearly indicates that the Belg season total monthly precipitation is expected to decrease by 2030 for all sites. Therefore, the projected decrease in Belg season precipitation will negatively affect long-cycle crop yield in the study sites. The decrease in the Belg season precipitation agrees with [2] who investigated the impact of predicted changes in precipitation and atmospheric carbon dioxide on maize and wheat yields in the Central Rift Valley of Ethiopia.

By contrast, despite some differences in the magnitude of changes, the total monthly precipitation is projected to increase for the Bega season (November, December, and January) for Melkassa by 2030. Even though some of the GCMs indicated an increase in the Bega season total monthly precipitation for Ambo and Bako, the GCMs ensemble evidently illustrated that the total monthly precipitation would remain almost the same as the baseline for Ambo and Bako by 2030. Overall, the projected increase and decrease in precipitation for the Bako and Melkassa sites, respectively are in agreement with [21,37]. Under normal conditions, the Bega season is a time for harvesting, particularly for the lower altitude areas [67]. Hence, the anticipated increase in monthly total precipitation mainly for November and December might affect the agricultural operation such as harvesting at Melkassa. Therefore, harvesting time should be adjusted accordingly for this site.

The projected air temperature showed that the study region will get warmer under the future climate compared to the historical period although the magnitude of change may vary depending on the site. Across the study sites, the average monthly maximum air temperature may increase by between 0.3 and 1.7, 0.7 and 2.2, and 0.8 and 1.8 °C for Ambo, Bako, and Melkassa, respectively during 2030 compared to the historical period. The expected increase in monthly average maximum air temperature by 2030 is greater for Bako compared to the other sites. This agrees with the previous reports that indicated future warming for the study sites [21,37]. Similarly, the average monthly minimum air temperature may change by between 0.6 and 1.7, 0.8 and 2.3, and 0.6 and 2.7 °C for the corresponding sites in the near future. The increase in minimum air temperature is expected to be higher at lower altitude (Melkassa) compared to those in mid and higher altitudes.

Rising maximum and minimum air temperatures played a crucial role in maize yield reduction which negatively impacts maize growth and development. For instance, the increased air temperature may lead to the shortening of the reproductive phases and reduce the available time for radiation interception and carbon assimilation as previously reported [68–70]. Authors of Ref. [68] projected a reduced period of 10 to 30 days for the grain-filling phase and a decrease in maize yield. Authors of Ref. [69] illustrated that for maize in the USA, there would be a decrease in days to flowering by 17 days and a yield loss of 13% if air temperature increased by 2 °C. Similarly, for the March, June, and November planting season in South Asia, authors of ref. [70] projected that an increase in maximum and minimum air temperatures by 1 °C caused a yield reduction of 55, 13, and 32% respectively while an increase of 5 °C caused a reduction of 98, 64, and 75% for the respective months.

The GCMs ensemble mean also indicated that the average monthly maximum air temperature by the 2030s will increase to between 24.0 and 29.7, 25.6 and 33.1, and 27.8 and 32.5 °C for Ambo, Bako, and Melkassa respectively. Similarly, the average monthly minimum air temperatures are expected to increase by between 10.1 and 13.2, 13.2 and 16.5, and 11.6 and 18.0 °C for the corresponding sites by 2030. In addition, the GCMs ensemble means clearly indicates that the increase in monthly average maximum air temperature in the 2030s will be less during the main rainy season (Kiremt) than that for the small rainy season (Belg) and the dry season (Bega) for all sites. The lower increase in average monthly air temperature during the main rainy season (Kiremt) may lead to reduced evaporation followed by reduced drying of the surface. Furthermore, by 2030 the monthly average minimum air temperature is expected to be higher during the Belg season for Ambo. Likewise, the monthly average minimum air temperature is anticipated to increase for both Belg and Kiremt seasons for Bako and Melkassa compared to the Bega season in 2030. The increase in maximum and minimum air temperatures for the study sites is in agreement with [21,37].

4.2. Impact of Climate Change on Maize Yield Compared to the Baseline

The average simulated maize yields of up to 12.5 t ha^{-1} for the baseline period (1995–2017) were comparable to measured maize yield of up to 6.7 t ha^{-1} across all cultivars and sites while simulated maize yield at Bako slightly higher (up to 15.5 t ha^{-1}) than the rest of the sites. This difference might have been associated with an increased annual total rainfall and decreased average maximum air temperature and evapotranspiration during the maize growing period at the Bako site (Supplementary Figures S4 and S5).

If the existing agronomic practices by farmers are not improved and/or continue in the near future, the simulated mean yield indicates that maize yields are likely to be negatively impacted by climate change at Melkassa and Ambo as compared to Bako by 2030. The impact was greatest for Melkassa (low altitude) where the air temperature is naturally high, and precipitation is low. The projected increase in air temperature and decrease in precipitation particularly during the main rainy season (Kiremt) might cause a maize yield reduction. The result is consistent with other studies [37,38]. Previous studies also indicated an increase in air temperature will cause an increase in maize development rate and a decrease in the total growth duration. This decrease limits the available time for the anthesis stage and leads to a depletion of kernels per plant which subsequently reduced the simulated yield in comparison to the baseline conditions [71]. Authors of Ref. [72] reported that further increases in air temperature may shorten crop life cycles and accelerate crop development rates, implying increased respiration losses, reduced biomass accumulation, and reduced crop yields. Authors of Ref. [73] also found that climate change will cause crops to complete their growth in a shorter period of time and this will result in a 10 to 30% reduction in yield in the future.

Climate change is likely to reduce maize yield at Ambo by an average of 4% in 2030 if the current varieties are grown under the existing agronomic practice in the near future. This could be associated with the decrease in precipitation and the increase in air temperature during the short rainy season (Belg) leading to yield reduction. Low maize yields have a direct impact on food security in the study areas. Rapid changes in basic crop management practices are necessary for the study areas and if not, farmers will be at risk of future climate shocks. Thus, improved crop management practice is needed for the maize cropping system to be more resilient to the changing environmental conditions [74].

On the contrary, future maize yield was projected to increase slightly relative to the baseline yield for Bako. This could be attributed to the increase in precipitation in the main rainy season (Kiremt) and the increase in air temperature which seemed to remain favorable for maize yield for this study site. This finding agreed with [21], who showed that future maize yield was slightly higher than the baseline yield at Bako.

4.3. Crop Management Practices as Adaptation Options

The challenge to produce enough food for the fast-growing population in Ethiopia will be greater under the changing climate unless the farming systems used involve adaptation strategies and/or new technological advancements are achieved. Since rainfed maize production is vital for food security in Ethiopia [18] adapting this cropping system to drier and warmer future climatic condition is important. In the future climate, maize would have a reduced time to flowering and to maturity due to the projected high maximum and minimum air temperature for the study sites. Therefore, adjusting planting date, nitrogen application level, and choosing the appropriate cultivar could be considered the three agronomic approaches which can be used to minimize the impact of climate change on maize and to increase yield.

Under future climate, early planting between 15 May and 01 June resulted in improved relative yields for all maize cultivars for Ambo. The result is supported by [71] who reported that early planting allows the maize crop to escape the hot weather of a future environment and increase yield compared to that for the local and late planting dates in the midlands of KwaZulu-Natal, South Africa. The increased N fertilizer level from 23–150 kg ha^{-1} resulted in improved yields for all cultivars when combined with early planting at Ambo. Nitrogen fertilizer is a key nutrient for crop growth to achieve the yield potential of new cultivars [75].

Nitrogen management together with a shift in planting dates were one of the most important adaptation strategies tested, in terms of yield impact for Bako. For example, early planting combined with a nitrogen fertilizer level of 23–100 kg ha^{-1} provided higher relative yields under the future climate. Delayed planting has a negative influence on maize production in the future climate.

Our results differed from [76] who suggested that combining high fertilizer levels with late planting resulted in increased yields for Bako. The differences could be due to the differences in the climate downscaling method used to produce future climate projections. This study used climate projection data downscaled dynamical RCM [59] while a simple delta factor method was used in [76]. In general, the results from the current study suggest that improvements in crop management practices could lead to increased yields.

All planting dates considered resulted in negative relative yields for Melkassa. However, late planting had reduced relative yields compared to early planting. Higher fertilizer levels (100–150 kg ha^{-1}) seem to reduce yield reductions under the future climate, but this varied among maize cultivars studied. Planting the Jibat cultivar between 15 and 30 June at higher N levels may reduce severe yield reductions of maize at Melkassa. The result agrees with [77] who showed that long-season cultivar can compensate for the reduced growth duration resulting from future increased air temperatures.

4.4. Crop and Climate Models Uncertainty in Yield Simulation

The AquaCrop (water-driven) model over-predicted maize yield in most cases during the simulation period for the study sites. This might be due to the simplification of complex processes in AquaCrop [78,79] as compared to DSSAT and APSIM (radiation-driven) models. In addition, the AquaCrop model has high extrapolative capability by allowing the normalized water productivity to account for climatic conditions and yield simulation [80]. Furthermore, there are several factors such as biotic and abiotic stresses [81] as well as pedo-climatic conditions [82] that are not accounted for in the models used and could have attributed toward the over-prediction of crop yield. On the other hand, DSSAT (radiation-driven) model underestimated maize yield for some cultivars for the study sites. This is explained by the performance of the DSSAT model varied amongst locations and cultivars [83]. For this study, compared to crop models, GCM uncertainty in predicted future maize yield is relatively larger. These results are consistent with other studies of climate change impact quantification on maize [37,84]. However, the result is in contrast to the findings of another study reporting that uncertainty from crop models was higher than those from GCMs [21,85,86].

5. Conclusions

This study quantifies the impact of climate change on maize production in tropical environments of Ethiopia and the role of crop management practices as an adaptation mechanism under future climate. The analysis of climate change scenarios of seven GCM models and RCP 8.5 indicates compromised climatic conditions for maize growth. The results indicate that both the average monthly maximum and minimum air temperature will increase in the study areas by 2030. The GCMs ensemble show that the monthly average maximum air temperature will increase during the Belg and the Bega seasons rather than the Kiremt season in 2030. The monthly average minimum air temperature may increase during the Belg season at all sites.

Monthly total precipitation will remain almost the same as the baseline while the Belg season monthly total precipitation will decrease at Ambo under the future climate. The Kiremt season monthly total precipitation, on the other hand, may significantly increase at Bako in 2030. However, future monthly total precipitation will reduce considerably for the Belg and Kiremt seasons at Melkassa in 2030. These would result in a mean maize yield reduction of 4 and 16% at Ambo and Melkassa respectively, and a mean maize yield increase of 2% at Bako in 2030.

The projected climate change, with increasing air temperatures and changes in precipitation, will become a threat to Ethiopian food production unless adaptation strategies are applied. In the higher altitude (Ambo), early planting of maize cultivars between 15 May and 01 June would result in improved relative yields in the future climate. Generally, combining early planting with an increase in fertilizer levels between 23 and 150 kg ha^{-1} will result in improved yields for all maize cultivars in Ambo. For the mid-altitude (Bako), planting after 15 May has either no or negative effect on maize yield. However, early planting combined with a nitrogen fertilizer level of 23–100 kg ha^{-1} provided higher relative yields under the future climate in Bako. Delayed planting has a negative influence on maize production for Bako under the future climate (2030). For the lower altitude (Melkassa), all planting dates considered resulted in a negative relative yield. However, late planting would have lower relative yields compared to early planting. Higher fertilizer levels (100–150 kg ha^{-1}) seem to reduce yield reductions under the future climate, but this varied among maize cultivars studied. Planting the Jibat cultivar between 15 and 30 June at higher N levels may reduce severe yield reduction of maize at Melkassa. The output of this study is important, since it can assist farmers to change their crop management practices and agricultural policymakers at the regional level for sustainable maize production in the study region.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/atmos14030497/s1, Figure S1. Percentage changes in monthly total precipitation of the projected climate by 2030s; Figure S2. Projected changes in monthly average maximum air temperature (°C) by 2030s; Figure S3. Projected changes in monthly average minimum air temperature (°C) by 2030s; Figure S4. Monthly total rainfall, average solar radiation, and the number of rainy days for the crop growing season 2017/2018; Figure S5. Monthly average maximum and minimum air temperature, and ETo for the crop growing season 2017/2018; Table S1. Main soil properties for the study areas used in the model simulation.

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Conflicts of Interest: The authors declare that they have no conflict of interest.

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