Impact of climate change on future barley (Hordeum vulgare L.) production in Ethiopia

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List of abbreviations and acronyms

AgMIP	Agricultural Model Intercomparison and Improvement Project
AOGCM	Atmosphere-Ocean General Circulation Models
CaC_{l2}	Calcium chloride
CH_4	Methane
CMIP5	Fifth Coupled Model Inter-comparison Project
DAP	Diammonium phosphate
EIAR	Ethiopian Institutes of Agricultural Research
GCM	Global Climate Models
GDP	Gross domestic product
GHGs	Greenhouse gases
GLUE	Generalized Likelihood Uncertainty Estimation
IPCC	Intergovernmental Panel on Climate Change
ISRIC	International Soil Reference and Information Centre
ITCZ	Inter-tropical Convergence Zone
K_2O	Potassium oxide
KCl	Potassium chloride
N_2O	Nitrous oxide
NAPA	National Adaptation Program for Action
NMA	National Meteorological Agency
nRMSE	Normalized Root Mean Square Error
P_2O_5	Phosphorus oxide
pH	Potential of hydrogen
PPM	Parts per million
RCP	Representative Concentration Pathways
RMSE	Root Mean Square Error
SSA	Sub-Saharan Africa

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1. Introduction

1.1. Climate change and its impact on primary production

Global warming is a problem caused by increased concentrations of greenhouse gases (GHGs), such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) in the atmosphere due to anthropogenic activities. As a result, global air temperatures rise, leading to the phenomenon known as climate change which is the most serious challenge of the 21st century (Adem & Amsalu, 2012; Vijayavenkataraman et al., 2012). Climate change has a significant effect on different sectors. The agricultural sector is one of the most sensitive and inherently vulnerable to climate variability, owing to its enormous size and sensitivity to weather parameters (Müller et al., 2011; Thornton et al., 2010, 2011). Climate change is defined as a change in the state of the climate that can be identified (for example, using statistical tests) by changes in the mean and/or variability of its properties and that lasts for an extended period, typically decades or longer. While climate variability refers to variations in the mean state and other climate statistics on all spatial and temporal scales beyond individual weather events. According to the most recent Intergovernmental Panel on Climate Change (IPCC) assessment report (AR6), global temperatures are expected to rise in tandem with CO_2 and ozone (O_3) concentrations (IPCC, 2021). CO_2 and O_3 emissions are expected to increase the frequency, length, and intensity of intra-seasonal extreme weather events such as heatwaves, floods, and storms as yearly temperatures rise (Krinner et al., 2013). Mankind is rapidly approaching a worst-case scenario known as RCP8.5 unless collective action is taken very soon (IPCC, 2014). According to projections, CO_2 will reach around 1,000 ppm by the end of the 21st century in the RCP8.5 scenario, and the global mean temperature will rise by about 5 °C (Krinner et al., 2013). Many regions of the world have already experienced greater regional-scale warming. The decade from 2011 to 2020 was the warmest, with the global average temperature reaching 1.1 °C above pre-industrial levels in 2019. Anthropogenic-caused global warming is currently increasing at a rate of 0.2 °C per decade (IPCC, 2021).

Sub-Saharan Africa (SSA) is the region in the world, most vulnerable to climate change. It is especially pronounced with intensified temperature extremes, precipitation anomalies, and natural disasters (IPCC, 2018). Temperatures on the African continent are expected to rise far faster than the global average during the 21st century (IPCC, 2007b; James & Washington, 2013; Sanderson et al., 2011). According to the IPCC, near-surface temperatures in West Africa and the Sahel have risen over the last 50 years (IPCC, 2014). Similarly, New et al., (2006) found that between 1961 and 2000, the number of cold days and nights decreased while the number of warm days and nights increased. A study by Collins et al. (2011) also showed statistically significant evidence of warming between 0.5 °C and 0.8 °C throughout 1970 – 2010 in Africa based on remotely sensed data. Uncertainty exists regarding rainfall projections for Africa (IPCC, 2014; Rowell, 2012), as well as projected changes across SSA for the mid and late 21st centuries. Downscaled projections indicate likely increases in rainfall and extreme rainfall by the end of the 21st century in regions with high or complex topography, such as the Ethiopian Highlands (IPCC, 2014). Annual precipitation in SSA, particularly in West Africa and the Sahel, is reported to be decreasing (Hulme et al., 2001; Nicholson, 2001). Rainfall in West Africa's semi-arid and sub-humid zones has been 15 – 40% lower on average over the last 30 years (1968 - 1997) than it was between 1931 and 1960 (Nicholson, 2001). The main reason for this uncertainty in rainfall projections is that most locations of the African continent do not have enough observational data to draw reliable conclusions about annual precipitation trends over the past century (IPCC, 2014).

Rising temperatures, precipitation fluctuation, and CO_2 fertilization have different effects depending on the crop, location, and extent of change in these factors (Malhi et al., 2021). Some impacts of climate change on barley physiology and yield are shown in Figure 1. The harvestable product of crops is projected to grow as CO_2 levels in the atmosphere rise, and plant developmental modifications will vary depending on the type of crop. C3 crops are predicted to produce more biomass, in the absence of severe conditions, and the water requirements of both C3 and C4 crops are expected to be reduced. However, the positive effects of increased CO_2 are anticipated to be counterbalanced by rising temperatures and changing precipitation patterns. Several studies conclude that climate change will have the greatest impact on agricultural economic output in Sub-Saharan Africa (Challinor et al., 2009; IPCC, 2007a; Müller et al., 2011). A reduction of crop yields by 6 – 24% is expected in the Sahel region countries of Burkina Faso, Ethiopia, Kenya, Senegal, Zambia, and Zimbabwe, except for maize, which showed a positive trend with increased temperature (Boubacar, 2012). The impact of rising temperatures on yield is shown to be reduced, whilst rising precipitation is predicted to offset or minimize the impact of rising temperatures. On average, each 1°C increase in temperature reduces the length of time it takes for plants to grow approximately by 7 days (IPCC, 2007a; Muchow, 1990). If both the temperate and tropical regions experience a 2 °C increase in mean surface temperature globally, yield losses in cereal grains are anticipated to worsen by up to 25% (Zhao et al., 2017). Plant–water relations are extremely responsive to changes in temperature and precipitation. Droughts are expected to become more common soon, with a projected increase in drought-affected land from 15.4% to

44.0% by 2100. By 2050, the output of main crops in drought-prone locations is anticipated to drop by more than half, and nearly 90% at the end of the century (IPCC, 2021).

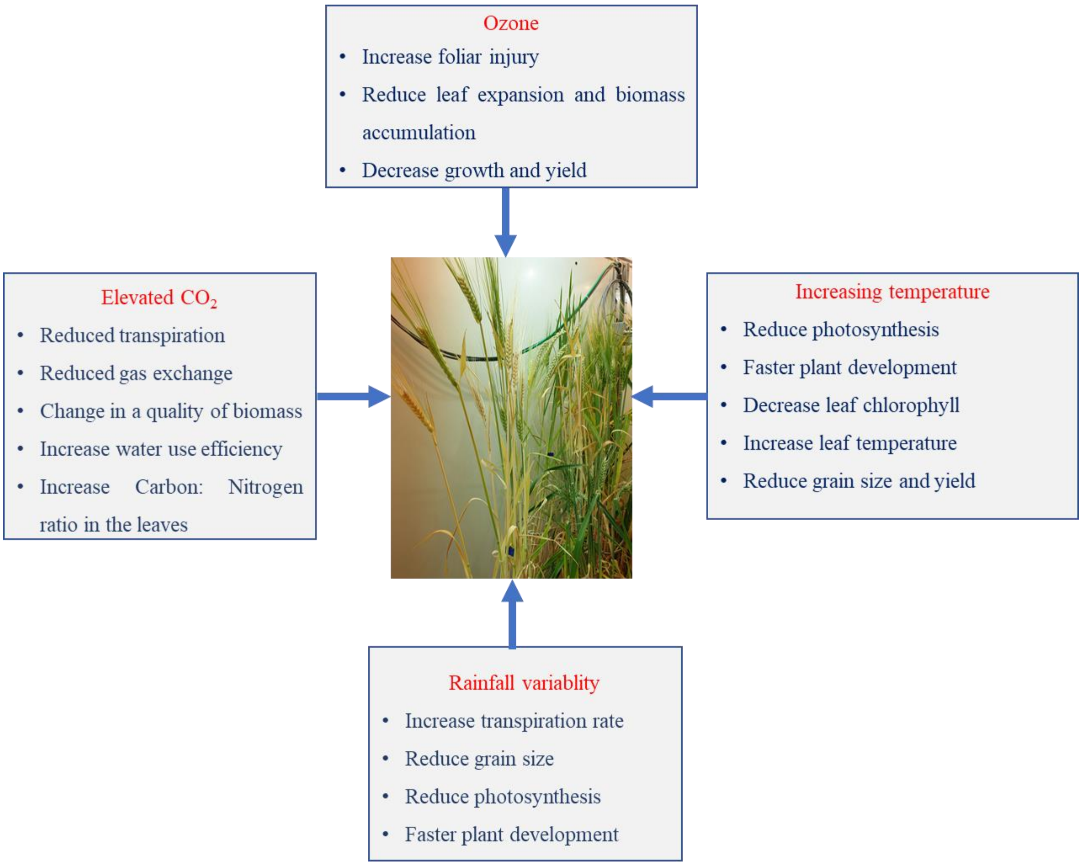

Figure 1: The impact of climate change on barley crop physiology and yield.

1.2. Overview of Ethiopian agriculture and climate

Ethiopia is located between 3°30' and 14°50' latitude and 32°42' and 48°12' longitude in north-eastern Africa. It covers over 1.13 million square kilometers and has elevations ranging from 125 meters below sea level to 4,620 meters above sea level (m.a.s.l). Agriculture provides a living for roughly 85% of Ethiopia's people, accounts for half of the country's GDP, and accounts for more than 80% of foreign exchange profits (Deressa & Hassan, 2009). Small-scale crop-livestock mixed farming systems predominate, and cereals are the most important food crops, accounting for 77% of total cultivated land (Arndt et al., 2011). Ethiopia has a wide range of climatic conditions, from humid to semi-arid. The seasonal migration of the inter-tropical convergence zone (ITCZ) and a complicated terrain play a key role in its climate system (NAM, 2001). The average annual rainfall distribution varies from more than 2,000 mm in the southwestern highlands to less than 300 mm in the south-eastern and north-western lowlands (Figure 1. a). The south-west and western regions of the country have a uni-modal rainfall pattern, while the rest of the country has a bi-modal pattern (World

Bank, 2006). The average annual temperature (Figure 1. b) ranges from around 15 °C in the highlands (>1500 m.a.s.l.) to more than 25 °C in the lowlands (< 1500 m.a.s.l.).

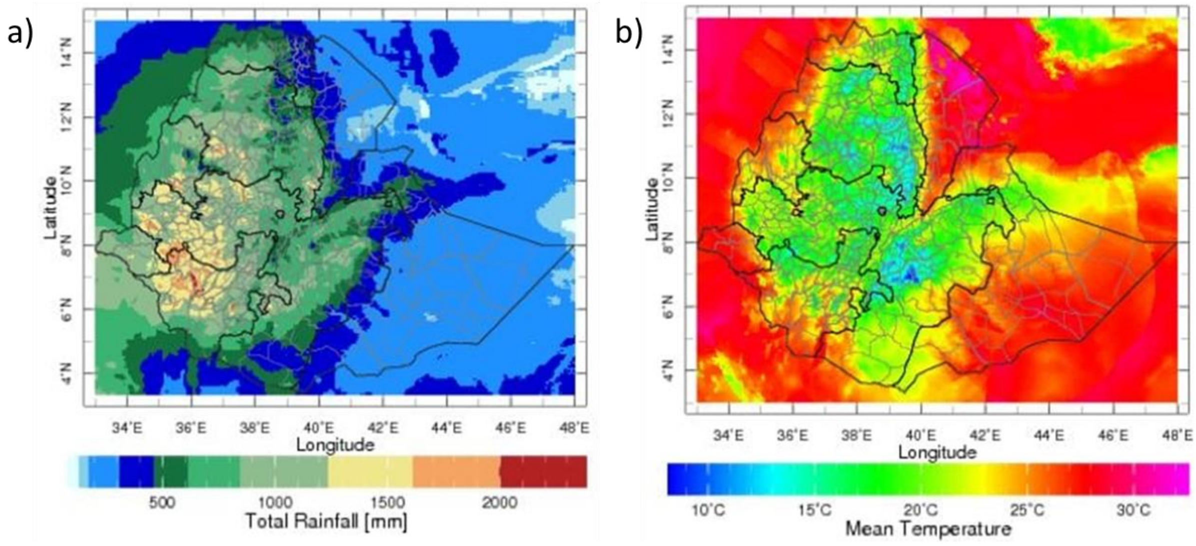

Figure 2: Rainfall (a) and mean temperature (b) distribution map of Ethiopia for the period 1981-2016 (Data source: National Metrological Agency).

Ethiopian agriculture, as well as the economy and climate in general, are inextricably linked. Depicts the relationship between rainfall variability and overall Gross domestic product (GDP) performance, years with low rainfall were linked with low total and agricultural GDP, whilst years with high rainfall were related to high total and agricultural GDP as shown in Figure 2 (World Bank, 2006). Food insecurity in Ethiopia has been caused by climate change, particularly rainfall variability and accompanying droughts (Rosell, 2011; Seleshi & Zanke, 2004). Climate change is projected to increase the number of obstacles and lower the economy's performance (Arndt et al., 2011). Ethiopia was identified as one of the countries most exposed to climatic variability and change in research on mapping poverty and vulnerability in Africa (Thornton et al., 2006).

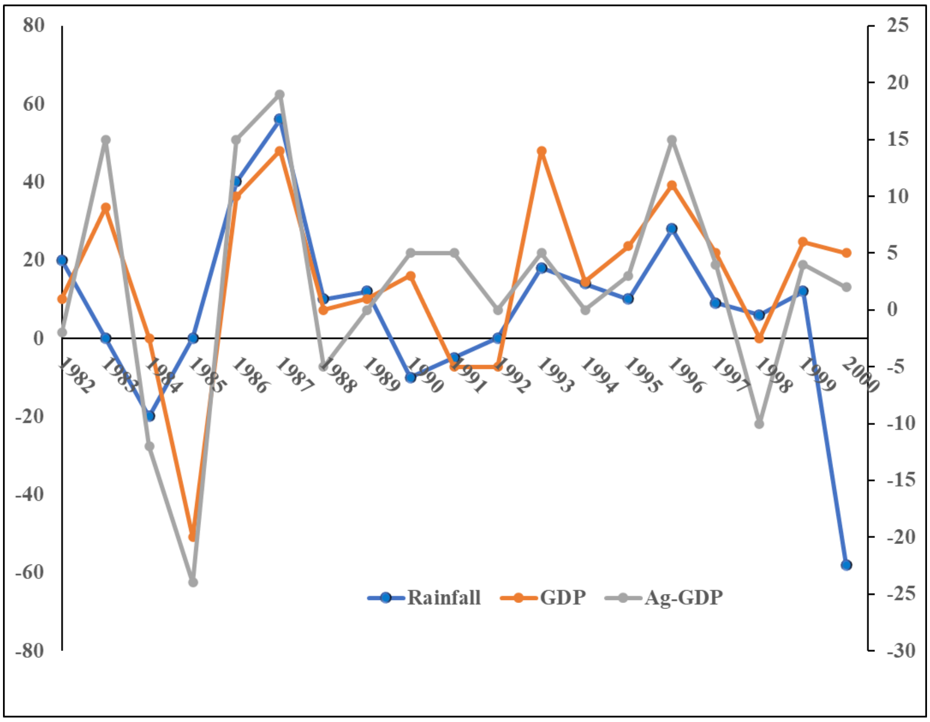

Figure 3: Effect of rainfall variability on the total gross domestic product (GDP) and agricultural growth domestic product (Data source: World Bank, 2006).

Ethiopia launched a National Adaptation Program for Action (NAPA) in 2007 after recognizing adaptation as a key response to the impacts of climate variability and change (NMA, 2007). Priority projects selected by the NAPA include institutional capacity improvement, natural resource management, irrigation agriculture, water harvesting, and weather early warning system strengthening. Ethiopia just released its blueprint for a climate-resilient economy (EPA 2011). Despite these policy efforts, there are few studies on the effects of climate change and adaptation alternatives, which may hinder policy formulation and decision-making when it comes to planning adaptation solutions. Some studies evaluated the effects of climate change on the Ethiopian economy (Arndt et al., 2011; Block et al., 2008; Dercon, 2004; Deressa et al., 2009; Mideksa, 2010), while others analyzed household vulnerability to climate change (Deressa et al., 2008; Yesuf & Bluffstone, 2007) and the factors that influence farmers' decision (Deressa & Hassan, 2009). However, there is a scarcity of data on biophysical impacts (e.g., changes in crop yields) and adaptation choices under various climate change scenarios, which is crucial for farmers to make informed decisions in a changing environment. For agricultural systems to adapt to future climate change, a quantitative understanding of existing climate variability, and its implications is critical. Furthermore, for Ethiopia's agricultural production and food security, forecasting future climate change consequences and evaluating potential adaptation measures for various climate change scenarios is critical.

1.3. Barley production and constraints in Ethiopia

Ethiopia is noted for having a lot of genetic variation in barley. The vast genetic diversity is due to a variety of agroecological environments, a long history of barley cultivation, and extensive cultural activities (Bekele et al. 2005). In a country like Ethiopia, where agroclimatic and growing circumstances highly vary, the existence of genetic diversity is especially important for enhancing production and maintaining diversity (Worede et al. 2000). Barley is grown in almost every part of the country, but it is primarily grown at high altitudes (2000 m.a.s.l.) and in some regions in two distinct seasons: Belg (February-May), which depends on the short rainfall period from March to April, and Meher (June-December), which depends on the long rainfall period from June to September (Lakew et al., 1997; Bekele et al. 2005). The Meher barley accounts for more than 85% of Ethiopia's total barley crop (Bekele et al. 2005). Ethiopia has large suitable cultivated land for barley production, which covers about 897,016 ha per year. It produces 226,126,5 tons of barley per year as shown in Figure 3 (FAOSTAT, 2021).

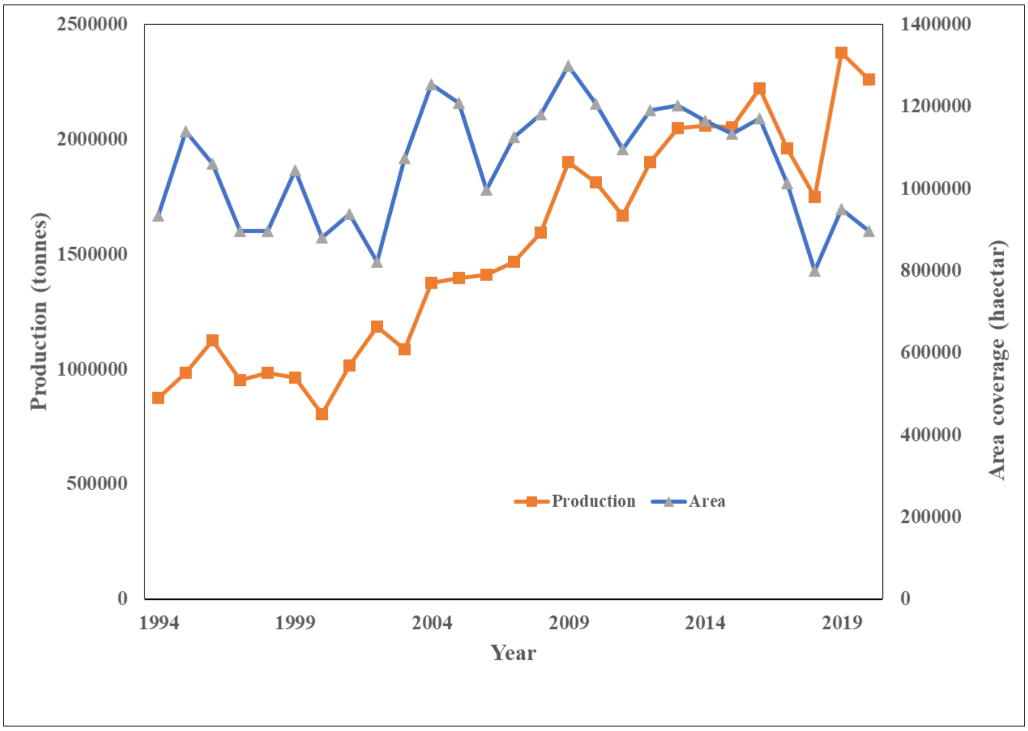

Figure 4: Barley production and location coverage in Ethiopia (Data source: FAOSTAT, 2021).

Even though barley can withstand more adverse growing conditions such as drought or low soil fertility, it still faces some production challenges. The most significant is the unpredictability of rainfall patterns, as well as a lack of improved seed and fertilizer supply (Begna et al., 2014; Cheung et al., 2008). The lack of reliable weather forecasts and communication routes for resource-poor farmers necessitates the development of cultivars that are resistant to such fluctuations. Released/modern cultivars are often genetically homogeneous and bred for high-yield levels in high-input environments (Newton et al., 2010). Landraces, on the other hand, are "dynamic population(s) of a cultivated plant with the historical origin, distinct identity, and a lack of formal crop improvement, as well as being genetically diverse, locally adapted, and associated with traditional farming systems" (Villa et al., 2005). As a result, landraces strive to provide genetic resources and plant traits that are well adapted to local environmental and cultural conditions. Farmers have maintained and selected landraces overtime to meet their personal economic, ecological, and cultural needs, and they have been cultivated in small-scale farming systems with low external factor input and high surrounding diversity (Teshome et al., 1997).

Landraces account for more than 90% of Ethiopia's cultivated barley diversity (Hadado et al., 2010), and they reflect a deeply rooted and ancient relationship between barley and Ethiopian farmers. The national agricultural system has failed to deliver significantly better-performing cultivars suitable for the cropping systems of resource-poor smallholder farmers and capable of replacing landraces (Mulatu and Lakew, 2011). As a result, understanding the yield stability of existing Ethiopian barley released cultivars and landraces under changing environmental variables is critical for future barley variety development. Furthermore, even though barley landraces are widely cultivated in Ethiopia and are thought to be an important source of genes for stability traits, scientific literature on their yield stability across variable environments is currently very limited. Because barley is primarily a self-pollinated crop, landraces are mixtures of mostly homozygous genotypes (Brown, 1978; Rodriguez et al., 2012), and landraces with higher mean grain yield can be easily utilized or used as a basis for further improvement that static stability is considered important by farmers and breeders value.

Studies on cereal crops that compared landraces and released cultivars observed greater static yield stability under different environments. For instance, a study by Wosene et al. (2015) comparing Ethiopian barley genotypes reported high yield stability for landraces compared to the released cultivars. Similar findings have been previously observed in maize (Salazar et al., 2007), wheat (Jaradat, 2013), and field crops in general (Oliveira et al., 2013). The greater genetic diversity of landraces contributes significantly to their increased stability (Ceccarelli, 1994). Under non-optimal farming conditions, results from field experiments show that landraces tend to yield the same or even higher than released cultivars (Noguera et al. 2011). In Burkina Faso, farmers have a strong interest in sorghum landraces due to their ability to produce secure and stable yields in the face of unpredictable climate conditions (Brocke et al. 2014). Field experiments from semi-arid and arid regions of South Asia and Africa comparing pearl millet landraces against modern varieties also showed that landraces yielded significantly more grain under drought stress than modern varieties (Yadav 2010). Released cultivars typically respond better to optimal environmental conditions than landraces (Pswarayi et al. 2008), and hybrids of winter barley demonstrated greater dynamic yield stability than lines (Mühleisen et al. 2014). The wide range of genotypes that respond with higher yield if the environment is improved was observed for both landraces and released cultivars (Wosene et al. 2015), which suggests that both types of genotypes can be significantly improved for dynamic stability.

1.4. Important Agro-morphological traits of barley

Agronomic traits such as the number of spikes per plant, number of grains per spike, and thousand-grain weight all contribute directly and indirectly to final grain output in cereal crops like barley (Fischer & Edmeades, 2010). Most yield components are complex features that are influenced heavily by the environment in which they grow. Grain yield is a more quantitative variable than yield contributing agronomic traits, hence environmental impacts, and genotype-by-environment (GxE) interactions have a stronger impact on grain yield (Baenziger et al., 2011). To develop higher-yielding cultivars, indirect selection on yield components may be more efficient than direct selection on grain yield (Puri et al., 1982). As a result, it is critical to classify and model current barley genotypes for the many settings that exist, as well as seek strong and reliable traits that can be utilized as a selection index.

Since multiple yield components with different GxE interactions and heritability values are available for selection, a key question is which combination of yield components improves genetic gain compared to direct selection of yield. Furthermore, if the relationship between traits is not static across environments or developmental stages, yield components compensate for each other in trait correlation dynamics. For example, when plant population density per unit location is low, more tillers are produced per plant (Herrera et al. 1994; de Rouw and Winkel, 1998). A lower number of spikes (fertile tillers) can be offset by a higher number of grains per spike (Lafond, 1994). When there is a partial loss of flowers due to pest or mechanical damage, the remaining flowers tend to develop larger grains with a higher thousand-grain weight. These compensation effects reflect phenotypic plasticity, which can help to maintain yield stability (Herrera et al. 1994; Berenguer and Faci, 2001).

To be considered a suitable trait for selection, a given yield component must have high heritability and a strong genetic correlation with overall grain yield. Several studies on barley trait correlations were conducted. For example, the number of fertile tillers and grains per spike had a significant effect on yield in 86 barley genotypes that were grown under rainfed conditions in Jordan for two years in a row (Al-Tabbal and Al-Fraihat, 2011). Another study conducted in Ethiopia over two locations and two consecutive years using 100 Ethiopian landraces and breeding material from the International Center for Agricultural Research in Dry Locations (ICARDA) found that the number of spikes per square meter, grain number per spike, and thousand-grain weight were the main yield components with positive and significant genotypic correlation coefficients to grain yield (Setotaw et al. 2014). These studies, however, were limited to a few locations or test environments. Given the high inter-annual rainfall variability in Ethiopian barley growing regions, which is exacerbated by ongoing climate change (Cheung et al. 2008), it is also necessary to consider the effect of sowing date on the relationship between agronomic traits, yield components, and yield to identify robust trait relationships suitable for selection. Because simple correlations between traits are highly dependent on environmental conditions, they cannot be used as the sole source of information for indirect selection. The genetic correlation must instead be extracted from the overall phenotypic correlation. The proportion of variance that two traits share due to genetic causes is referred to as genetic correlation, and it indicates to what extent measurements of one trait contain information about other traits (Thompson and Meyer, 1986).

1.5. Adaptation of cropping systems

Exploring climate change adaptation solutions to boost agricultural productivity and food security in vulnerable countries, such as Sub-Saharan Africa, is a serious priority. Cropping system adaptations have been reported to be promising in mitigating the detrimental effects of climate change on primary production (Anwar et al., 2013; Olesen et al., 2011). Numerous studies revealed that adaptation to climate change could substantially minimize negative impacts on agricultural production (Adger et al., 2005; Howden et al., 2007; Mertz et al., 2009; Smit & Skinner, 2002). Adaption research involves evaluating management choices under present and future climatic conditions, which is critical for decision-makers to identify appropriate adaptation strategies and support them with science-based and informed policies. Developing countries, such as Ethiopia, have responded to increased global attention on climate change adaptation by developing NAPA, which identifies priority locations for adaptation research and development (Coumou & Rahmstorf, 2012; Dow et al., 2013). Ethiopian NAPA encourages the development of a climate-resilient economy by assisting with adaptation at the national, regional, and local levels. Changes to planting dates, crop varieties, plant density, and nutrient and water management practices are all examples of possible adaptations (Rickards & Howden, 2012). These modifications are expected to significantly reduce the negative impact of climate change on crop yields, thereby reducing vulnerability (Easterling, 2007).

Farmers in East Africa have already implemented marginal adaptation measures such as changing planting dates and crop varieties; however, soil, water, and land management practices have not been widely adopted (Kristjanson et al., 2012). Soil and water conservation are especially important because they can improve the effectiveness of irrigation, fertilizer, and improved seeds (Kato et al., 2011). When incremental adaptations are no longer sufficient, farmers may be forced to implement systems adaptation (such as switching to resilient crops, crop diversification, or precision agriculture).

1.6. Outline, objectives, and design of the study

This dissertation was performed as part of the project Climate Change Effects on Food Security (CLIFOOD). The objective of the project, in general, is helping to achieve Sustainable Development Goals (SDGs) which are related to the core locations: i) to end hunger and poverty and ensure human dignity, equality, and health and ii) environmental protection. The project is under the Deutscher Akademischer Austauschdienst German Academic Exchange Service (DAAD program: Bilateral SDG Graduate School funded by the Federal Ministry for Economic Cooperation and Development (BMZ), funding code 57316245. Barley is chosen for the project because it is the fourth most important cereal crop in the world after wheat, maize, and rice. It is used as a food and beverage in more than 20 different ways in Ethiopia. The country is considered a center for barley diversity with the widest morphological diversity (Lakew et al., 1997). The existence of genetic diversity has special significance for improving productivity and maintenance of diversity in a country like Ethiopia under climate change (Worede et al., 2000). Barley genetics are well understood, and modern genetics methods may be used on it.

The general aim of this Ph.D. research is to investigate the impact of climate change on barley production. And to characterize trends, variability, and changes in agro-climatic conditions of the barley-producing locations in Ethiopia. The specific objectives were:

1. to synthesize and summarize the mean response of barley yield variables to eCO_2, temperature, N fertilization, and their interactions

2. to determine whether different CO_2 exposure methods, rooting conditions, or genotypes significantly alter the mean response of barley to eCO_2

3. to evaluate the performance of Ethiopian landrace and released barley cultivars growth, yield formation, and water-use efficiency under current and future CO_2 concentrations

4. to calibrate and evaluate the performance of the DSSAT-CERES-Barley model

5. to quantify climate-induced yield variability and yield gaps for rainfed barley production in Ethiopia

6. to explore adaptation options under different climate change scenarios for barley production systems in Ethiopia

To achieve the above-mentioned objectives different research approach methods were carried out during 2018 - 2022. A meta-analysis study was conducted using previously published peer-reviewed articles which focus on the response of barley to eCO_2 to address the first three objectives. The fourth objective was addressed with a climate chamber experiment applying two levels of CO_2 concentration representing the current and the future on a set of 30 Ethiopian barley genotypes (15 landraces and 15 released cultivars). The DSSAT-CERES-Barley model was calibrated and used to simulate climate change projections and impacts in Ethiopia considering potential barley-producing locations and two Ethiopian barley cultivars. In addition, adaptation options for barley production under climate change were modeled to address the research objectives listed 4 - 6. The first publication presents the response of barley yield parameters to eCO_2 as well as its interaction with different levels of temperature and N. The effect of the treatments was summarized and discussed. In addition, different factors such as genotype and experimental condition which might potentially affect the response of barley to eCO_2 were analyzed and presented. Publication two shows the results of a climate chamber experiment. The response of Ethiopian barley genotypes (landraces and released cultivars) growth, yield formation, and water use efficiency were presented. The third publication deals with a simulation of climate change and its impacts on crop production in Ethiopia. Two Ethiopian barley genotypes and four barley-producing locations in Ethiopia were considered in this study. The projected changes in climate and barley production were presented and discussed. In addition, adaptation options were also analyzed and presented.

2. Publications

Three scientific papers create the overall frame of the present cumulative dissertation. Among the three papers, two papers have been published and one paper is under revision in peer-reviewed international journals. The papers form the body of the thesis are presented in Chapters 3-5. All three papers are listed below and for citation of the two papers, please use the references given below:

Publication I

Gardi, M. W.; Haussmann, B. I. G.; Malik, W. A.; Högy, P. Effects of elevated atmospheric CO_2 and its interaction with temperature and nitrogen on yield of barley (*Hordeum vulgare* L.): a meta-analysis.

DOI:10.1007/s11104-022-05386-5 (Impact factor in 2021: 5.44)

Publication II

Gardi, M.W.; Malik, W.A.; Haussmann, B.I.G. Impacts of Carbon Dioxide Enrichment on Landrace and Released Ethiopian Barley (*Hordeum vulgare* L.) Cultivars. *Plants* 2021, 10, 2691.

DOI: 10.3390/plants10122691 (Impact factor in 20221: 3.94)

Publication III

Gardi, M. W.; Memic, E. Zewdu, E.; Graeff-Hönninger, S. Simulating the impact of climate change on barley yield in Ethiopia with the DSSAT-CERES-BARLEY model. *Agronomy Journal* 2022.

DOI: 10.1002/agj2.21005 (Impact factor in 2021: 2.65)

3. Publication I

Effects of elevated atmospheric CO_2 and its interaction with temperature and nitrogen on yield of barley (*Hordeum vulgare* L.): a meta-analysis

Gardi, M. W.; Haussmann, B. I. G.; Malik, W. A.; Högy, P. Effects of elevated atmospheric CO_2 and its interaction with temperature and nitrogen on yield of barley (*Hordeum vulgare* L.): a meta-analysis.

In chapter 3, the response of barley yield parameters to eCO_2 as well as its interaction with different levels of temperature and N were analyzed and summarized using meta-analysis techniques. The aim of this study was (1) to synthesize and summarize the mean response of barley yield variables to eCO_2, temperature, N fertilization, and their interactions; (2) to determine whether different CO_2 exposure methods, rooting conditions, or genotypes significantly alter the mean response of barley to eCO_2. Scopus, Science Direct, and Google Scholar were used to search for peer-reviewed primary literature on barley yield responses to eCO_2, temperature, and N using different keywords. Five barley yield variables (aboveground biomass, grain number, grain yield, thousand-grain weight, and harvest index) were included in the analysis. The magnitude of the CO_2, temperature, and N treatment effects on the selected variables, was determined using log response ratio as effect size. The results revealed that eCO_2 led to a significant increase in aboveground biomass, grain yield, and number of grains per plant. However, under limited N availability (50 kg ha^{-1}) the responses of aboveground biomass, grain number, and grain yield to eCO_2 were decreased. The magnitude of the CO_2-induced effect on barley grain yield will, in general, be determined by future atmospheric CO_2 concentrations as well as agronomic practices such as genotype selection and growing conditions. Uncertainties remain regarding the responses of barley yield variables to environmental stress, particularly aboveground biomass, the number of grains, and grain yield, which were all significantly affected. Field and laboratory experiments that better characterize the responses of barley to eCO_2 and its interaction with other stressors can help to better understand and with that reduce uncertainties in adapting future food production systems due to climate change.

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https://doi.org/10.1007/s11104-022-05386-5

REGULAR ARTICLE

Effects of elevated atmospheric CO_2 and its interaction with temperature and nitrogen on yield of barley (*Hordeum vulgare* L.): a meta-analysis

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Abstract
Aims The general aim of this meta-analysis is to synthesize and summarize the mean response of barley yield variables to elevated CO_2 (eCO_2) and how temperature and nitrogen (N) affect the CO_2-induced yield responses of barley.
Methods A meta-analysis procedure was used to analyze five yield variables of barley extracted from 22 studies to determine the effect size and the magnitude concerning eCO_2 and its interaction with temperature and N.
Results CO_2 enrichment increased aboveground biomass (23.8%), grain number (24.8%), and grain yield (27.4%). The magnitude of the responses to eCO_2 was affected by genotype, temperature, nitrogen, and CO_2 exposure methods. Genotype "*Anakin*" shows the highest CO_2 response of aboveground biomass (47.1%), while "*Bambina*" had the highest grain number (58.4%). Grain yield response was observed to be higher for genotypes *"Alexis"* (38.1%) and *"Atem"* (33.7%) under eCO_2. The increase of aboveground biomass and grain yield was higher when plants were grown under eCO_2 in combination with higher N (151–200 kg ha^{-1}). The interaction between eCO_2 and three different temperature levels was analyzed to identify the impacts on barley yield components. The results revealed that the CO_2-induced increase in grain number and grain yield was higher in combination with a temperature level of 21–25 °C as compared to lower levels (< 15 and 16–20 ℃). The response of barley yield to eCO_2 was higher in growth chambers than in other CO_2 exposure methods. Moreover, a higher response of aboveground biomass and grain yield to eCO_2 was observed for pot-grown plants compared to field-grown.

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Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11104-022-05386-5.

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Conclusions Overall, results suggest that the maximal barley production under eCO_2 will be obtained in combination with high N fertilizer and temperature levels (21–25 °C).

Keywords Climate change · Systematic review · Global change · *Hordeum vulgare* L. · Yield variables

Introduction

One of the most important challenges of the twenty-first century is to find solutions to the problems caused by global climate change. Alleviating future food security challenges will need to estimate crop production response to the ongoing increase of atmospheric carbon dioxide (CO_2), together with rising temperature, and soil fertility. Evidence indicates that atmospheric CO_2 concentration increased globally, from 280 ppm in the pre-industrial period to about 419 ppm in 2021 and it might increase to 550 ppm by 2050 (IPCC 2021). CO_2 is the most important anthropogenic greenhouse gas (GHG) and it represented 74% of overall anthropogenic GHG emissions in 2018 (IPCC 2021). The changes in CO_2 concentration and other GHG emissions are expected to increase air temperature by 2.5 to 4.8 °C at the end of the twenty-first century (IPCC 2021). These environmental changes will have a substantial effect on crop growth and food supply in the future. At the same time, the total global food production has to increase by 25 to 70% within the next 40 years, to meet the food demand for the projected increase in the global population (Fróna et al. 2019; United Nations 2011). As the raw material for plant photosynthesis, an increase in CO_2 concentration will inevitably affect the growth and development of plants. An increase in atmospheric CO_2 generally exerts beneficial effects on plant biomass by increasing net photosynthesis by 30 to 50% and reducing photorespiration (Drake et al. 1997; Poorter and Navas 2003; Schapendonk et al. 2000). This has been studied for cereals including barley, wheat, rice, oat, and rye (Conroyac et al. 1994; Kimball et al. 2002; Long et al. 2006). For instance, in a meta-analysis comprising 79 crops and wild species, Jablonski et al. (2002) documented an increase in yield of 28% averaged across crops and wild species due to elevated CO_2 (eCO_2). A climate chamber experiment with 700 ppm CO_2 on barley reported an increment of grain yield by 54% compared to 400 ppm (Alemayehu et al. 2014), while 47% enhancement of grain yield averaged across two genotypes was reported by Schmid et al. (2016) under eCO_2 level of 550 ppm. Moreover, Manderscheid and Weigel (2006) evaluated the effects of eCO_2 on barley using Free-air CO_2 enrichment (FACE) at 550 ppm, and obtained yield increases of 7 and 15% under the combination of eCO_2 with low and high N supply respectively.

The projected increase in biomass and grain yield of C3 crops due to eCO_2 is affected by certain environmental factors such as rising air temperature and nitrogen (N) (Jaggard et al. 2010; Weigel et al. 1994). Despite a good response of C3 crops production to eCO_2 at near-optimal temperature (18–23 ℃), the impact may be countered by rising temperature by 2–4 ℃ (Ainsworth 2008; Peng et al. 2004; Lobell and Field 2007; Tao et al. 2008). Accordingly, Dieleman et al. (2012) and Wang et al. (2012) have highlighted the relevance of the interactive impacts of eCO_2 and temperature on rice yield, but no particular meta-analysis addressing barley has been undertaken. In general, increased temperature is primarily linked with higher evapotranspiration, acceleration of plant development, and consequently shortening of developmental phases, leading to early maturation and decreased yields (Barnabás et al. 2008; Cox et al. 2000; Hansen et al. 2000; Högy et al. 2013; Mangelsen et al. 2011; Vara Prasad et al. 2002). Studies on six major crops including barley have indicated that increasing the seasonal average temperature by 1 °C results in a significant grain yield reduction by 4 to 10% (Barnabás et al. 2008; Hatfield et al. 2011). Clausen et al. (2011) found a grain yield reduction of barley by 14% under eCO_2 and elevated temperature (+3 °C) in comparison with the same level of eCO_2 and ambient temperature. A 53% reduction in grain yield of barley was recorded by another study due to elevated temperature in combination with eCO_2 (Alemayehu et al. 2014).

Elevated CO_2 typically leads to a marked increase of biomass in well-fertilized plants (Bowes 1996), this response is modified when the N fertilization is suboptimal. Among the various environmental factors, N availability can have a significant impact on crop biomass and yield formation in response to eCO_2 (Stitt and Krapp 1999; Kimball et al. 2002). Several studies have revealed CO_2 and N interactions, and it is widely assumed that N deficiency acts as a growth inhibitory factor, potentially decreasing the relative response to eCO_2 (Ainsworth and Long 2005). In general, studies address biomass accumulation under eCO_2 and variable N supply levels across cereal production (Reich et al. 2006). According to Ziska and Bunce (2007), there is now enough evidence to suggest that crop yield stimulation by eCO_2 is dependent on N availability. For example, this has been shown for barley (Kleemola et al. 1994) and wheat (Wolf 1996) and in chamber studies. However, some recent studies with rice that examined crop responses under FACE conditions and low N availability reported similar yield stimulation by eCO_2 as under sufficient N supply (Kim et al. 2003, Liu et al. 2008; Yang et al. 2009). There are still uncertainties whether this holds true also for other crops under field conditions.

Even though the pattern of yield response to eCO_2 and its interactions with temperature and N are similar within C3 crops, distinctions are evident across species, genotypes, and growing conditions (Connor 2002). The yield response of crops to eCO_2 is widely affected by enclosure systems and rooting conditions. Open-top chambers (OTC) have been widely used in eCO_2 field experiments but also questioned since they alter the micro-climate of the plants and thus may modify the magnitude of crop responses (Schimel 2006) . Comparison of conditions in OTCs to the open field show that temperatures and vapor pressure deficits are higher inside chambers and airflow is altered in the plant canopy (Ziska and Bunce 2007). The use of OTCs will also reduce transmission of solar radiation and shift the ratio between diffuse and total radiation (Rawson 1995). FACE systems have been developed to create a less artificial experimental setup compared to enclosure systems like OTCs. On the other hand, FACE systems have the drawback of not being able to reach strongly elevated concentrations for eCO_2 treatments and possibly less stable concentration levels that may lead to underestimation of plant eCO_2 responses (Leakey et al. 2009). However, eCO_2 concentrations are often lower in FACE (e.g., 550 ppm) as compared to OTCs or climate chambers (> 600 ppm). It is not clear whether OTCs or FACE studies showed larger effects of elevated CO_2 on crop biomass and yield than studies performed in greenhouses or growth chambers. Plants in both greenhouse and climate chambers should be subject to edge effects like those in OTCs (Long et al. 2004). Furthermore, it is questionable whether results from experiments with plants grown in pots can be comparable to field conditions since the response to eCO_2 might be reduced due to the restricted rooting volume and the pot size (Loladze 2014; Högy and Fangmeier 2008). Field-grown wheat had similar or lower responses to eCO_2 than plants grown in a pot (Wang et al. 2013). This contradicts the premise that restricted root development, nutrient, and water supply in pot studies leads to a decrease in photosynthesis and, as a result, a reduction in plant responsiveness to eCO_2 (Arp 1991; Curtis and Wang 1998).

Barley (*Hordeum vulgare* L.) is one of the most important and extensively cultivated cereal crops worldwide for human nutrition and as animal feed. The production of barley in 2020 was about 150×10^6 tonnes and it has been cultivated in more than 100 countries worldwide (FAOSTAT 2020). However, despite its importance, the effect of eCO_2 and its interaction with temperature and N fertilizer on barley production has not been quantitatively reviewed using meta-analysis techniques. Previous meta-analytic studies on C3 crops, such as wheat, rice, and soybean, have provided insights into the extent of the effects of eCO_2 on yield variables such as aboveground biomass, grain yield, grain number, thousand-grain weight, and harvest index (Ainsworth 2008; Broberg et al. 2019; Feng et al. 2008). The rationale for a meta-analysis is that, by combining the samples of the individual studies, the overall sample size is increased, thereby improving the statistical power of the analysis as well as the precision of the estimates of treatment effects. Several studies have investigated the effects of eCO_2 and their interactions with temperature and N on barley (e.g., Weigel and Manderscheid 2012; Manderscheid et al. 2009; Fangmeier et al. 2000). However, inconsistency in the findings and estimation of the effects in individual studies was noticed. For the first time to our knowledge, the response of barley to eCO_2 and its interaction with temperature and N as well as the effect of growing condition (CO_2 exposure methods, rooting volume) or genotype is quantitatively reviewed. The objectives of the present meta-analysis are therefore two-fold (1) to synthesize and summarize the mean response of barley yield variables (i.e. aboveground biomass, grain yield, grain number, thousand-grain weight, and harvest index) to eCO_2, temperature, N fertilization, and their interactions, and (2) to determine whether different CO_2 exposure methods, rooting conditions, or genotypes significantly alter the mean response of barley to eCO_2.

Materials and Methods

Database development

Peer-reviewed primary literature focusing on barley yield responses to eCO_2, temperature, and N were searched on Scopus, Science Direct, and Google Scholar. The search strings used to search the literature on the search engines are presented in Appendix 1. The search was intended to be comprehensive, including all relevant studies that were published between 1991 and 2020. The response of five yield variables (aboveground biomass, grain number, grain yield, thousand-grain weight, and harvest index) of barley were included in the database as well as in the search strings. The following four inclusion criteria were applied for including studies in the database: (1) the ambient CO_2 (aCO_2) level had to be ≤ 450 ppm (intended to represent the past and the near future concentration) and the eCO_2 has to be ≥ 451 ppm (representing CO_2 concentration in the future); (2) at least one of the selected yield variables is evaluated; (3) the response means, and sample sizes (n) are reported directly in the text, table or can be indirectly derived from figures, and (4) the CO_2 exposure technique is specified. Publication bias was checked by looking at the symmetry in a funnel plot (Appendix 2, Fig. 9. The final database covered a total of 22 studies that included CO_2, temperature, and N treatments over the entire experimental period (Fig. 1). Out of the 22 studies, 84 observations were extracted and analyzed. From these 84 observations, 42 was on the response of barley to eCO_2 as a single factor, 18 on the interaction of eCO_2 with temperature, and 34 on the interaction of eCO_2 with N. Observations were considered as independent within studies, if measurements were taken on different CO_2 concentration levels, genotypes, or combinations with N and temperature following previous meta-analysis studies (Ainsworth et al. 2002; Gurevitch and Hedges 1999).

To test the interaction effect of eCO_2 with temperature and N, we extracted data only from studies that included CO_2, temperature, and N treatments. For experiments involving additional environmental factors, such as O_3 and drought, the mean of the controls group was used. For each response variable, means and sample size were recorded from the treatment and control groups for each observation. The response of barley yield variables to eCO_2 might be affected by different moderators, thus the data were grouped into several groups, such as CO_2 fumigation methods (growth chamber, GC; greenhouse, GH; open-top chamber, OTC; and Free-air CO_2 enrichment, FACE), CO_2 levels (451–550, 551–650, and 651–720 ppm), air temperature levels (< 15, 15–20, and 21–25 °C), N fertilizer levels (0–50, 51–100, 101–150, and 151-200 kg ha^{-1}), growing conditions (pot-grown and field-grown), and genotypes. Sixteen genotypes were found in several studies, and they were used for the analysis of the CO_2 effects on the response of barley yield variables (Table 1). However, in addition to these 16 genotypes, a group of spring cultivars and accessions were used for the overall non-genotype-based analysis. For the analysis of all categorical variables including the interaction of eCO_2 with temperature and N, averaged eCO_2 was used across all levels.

Meta-analysis

Meta-analysis commonly describes the extent of an experimental treatment mean ($\bar{y}_T$) relative to the control treatment mean ($\bar{y}_C$) (Ainsworth et al. 2002). The log response ratio (mean yield of the experimental to the control group) was used as the effect size to calculate the magnitude of CO_2, and its interaction with temperature and N treatment on the selected yield variables of barley. The log transformation can make the data better approximate to the normal distribution, reduce skewness, and make non-linear relationships linear. For each treatment (eCO_2, eCO_2 with temperature, and N), we calculated the natural logarithm of the ratio as, $r = \bar{y}_T/\bar{y}_C$ and its percentage change from the control ([r-1] × 100). Thus, the expected mean percentage change is positive for $r > 1$ but negative for $r < 1$. Linear mixed models were fitted, assuming that differences among studies within a treatment combination are due to both sampling error and random variation. As variance or related parameters were not reported in several studies, unweighted analyses were performed for all the variables. However, resampling and bootstrapping techniques were used to obtain the confidence intervals of the mean effect

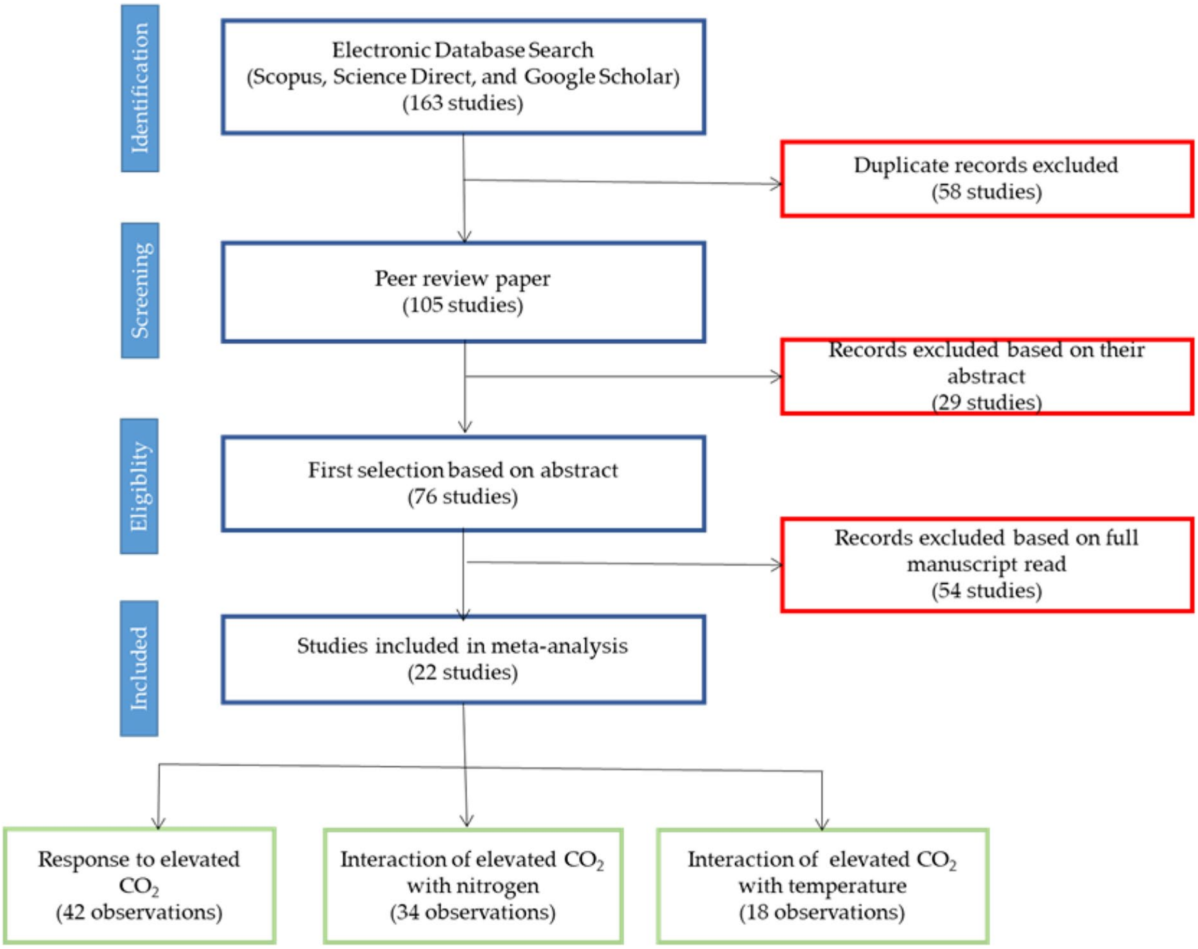

Fig. 1 PRISMA flow diagram for studies selection

size (Gurevitch and Hedges 1999). For each categorical variable, between-group heterogeneity (QB) was examined. The significance of the mean differences from categorical variables was tested (Gurevitch and Hedges 1999). All the analyses were performed in R statistical software (R Core Team 2019). The linear mixed model was fitted using the R library l*me4*.

Results

CO_2 effect on barley yield variables

Across all the 42 observations out of 22 studies, a significant enhancement in most of the measured yield components was observed at eCO_2 levels (i.e., 451–720 ppm) relative to aCO_2 ($\leq$450 ppm). Aboveground biomass of barley was increased by 23.8% [CI: 18.0–27.8%] under eCO_2 compared to barley plants grown under aCO_2. Grain yield was increased by 27.4% [CI: 18.5–36.2%], mainly due to higher grain number (24.8% [CI: 17.7–31.9%]) and thousand-grain weight (5.6% [CI: 3.5–8.1%]), however, the response of harvest index was not affected by eCO_2 (Fig. 2). The response of barley yield components varied with eCO_2 concentration levels (Fig. 3). For instance, the highest percent enhancement of aboveground biomass (28.7%) was observed under the eCO_2 concentration level of 551–650 ppm (Fig. 3). Under 451–550 ppm, aboveground biomass was increased by x%. Due to data limitations, the response of aboveground biomass was not evaluated under the highest eCO_2 level (651–720 ppm). Significantly higher positive responses of grain yield, grain

Table 1 List of barley genotypes found in the studies

Genotypes	Number of studies	Genotype description
Accessions*	10	A group of landrace accessions from different areas
Alexis	9	Two-row modern German malting barley cultivar, heat tolerant
Arena	4	Two-row Australian modern spring barley cultivar, powdery mildew tolerant
Anakin	9	Modern spring barley cultivar
Atem	4	European modern spring cultivar, drought tolerant
Aura	5	Spring malting barley cultivar, disease-tolerant old cultivar
Bambina	6	Mid-maturing modern spring cultivar
Gairdner	8	Australian malting barley, moderately tolerant to powdery mildew
Gammel-Dansk	2	Old landrace
Golden_Promise	4	Short height, high yields, and early maturing old cultivar
Harrington	4	High yielding and strong strawed old cultivar
Iranis	4	Salt tolerant Iranian old landrace
Kathleen	2	High yielding, mildew, and brown rust tolerant modern cultivar
RCLS-89	2	Two-row North American modern malt barley
Scarlett	4	Two-row modern German spring malting barley
Spring cultivars*	8	A group of spring cultivars from different areas
Theresa	16	Winter barley old cultivar
Thule	2	Six-rowed European old cultivar

* These groups of cultivars are not included in the genotype-specific analysis

number, harvest index, and thousand-grain weight were observed under the highest eCO_2 concentration level (651–720 ppm) relative to all the lower levels (Table 2 and Fig. 3).

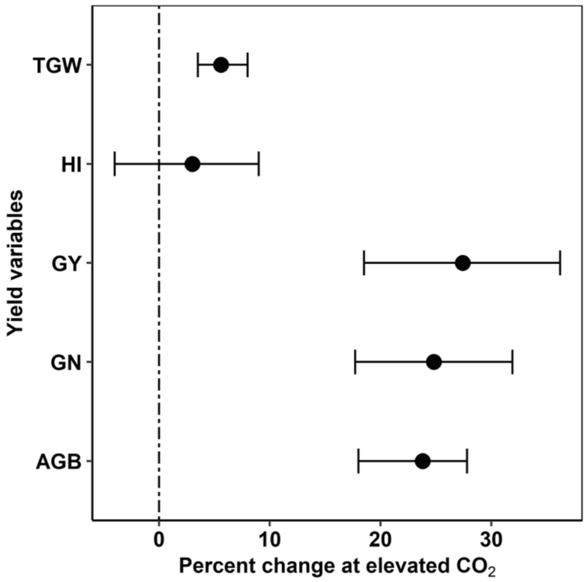

Fig. 2 Relative percentage change in barley yield response to eCO_2 analyzed out of 42 observations. The symbols represent the percentage change (±95% CI) in response relative to the corresponding control. TGW: thousand-grain weight; HI: harvest index; GY: grain yield; GN: grain number; AGB: aboveground biomass

Interaction of eCO_2 with N fertilization and temperature treatments

The response of barley yield components to eCO_2 was significantly affected by N fertilizer and temperature treatments (Table 2). The results from the interaction of eCO_2 with N showed an increase of yield components with increasing N level except for thousand-grain weight and harvest index. The highest responses of aboveground biomass (57.4% [CI: 54–62%]) and grain yield (58.7% [CI: 55–63%]) to eCO_2 were observed under the N level of 151–200 kg ha^{-1}, relative to lower N levels (Fig. 4). Grain number was increased by 28.8% due to eCO_2 under the application of 51–100 kg ha^{-1} N, which is not significantly different from the response under N level (151–200 kg ha^{-1}) as shown in Fig. 4. The response of thousand-grain weight and harvest index to eCO_2 were not significantly different between the N levels.

In comparison, aboveground biomass was increased, under the combination of eCO_2 with 15–20 °C (38.5% [CI: 34–43%]) compared to temperature levels < 15 and 21–25 °C (Fig. 5). On the other

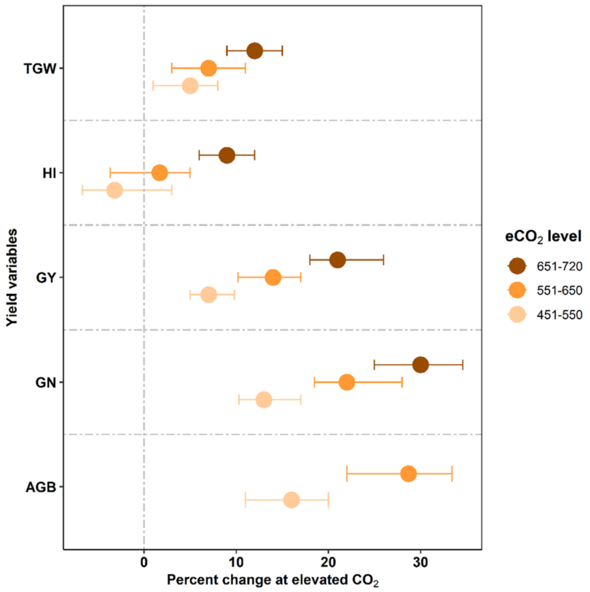

Fig. 3 Relative percentage change in barley yield response to three levels of CO_2 treatment (451–550, 551–650, 651–720 ppm) analyzed out of 42 observations on the response of yield variables/parameter to eCO_2. Due to a lack of data, the response of aboveground biomass to the highest level of CO_2 concentration was not evaluated. The symbols represent the percentage change (±95% CI) in response relative to the corresponding control. TGW: thousand-grain weight; HI: harvest index; GY: grain yield; GN: grain number; AGB: aboveground biomass

hand, we observed a mixed trend in the response of barley yield components to eCO_2 in combination with different temperature levels. Grain number (36.4% [CI: 29–41.4%]), and grain yield (59.7% [CI: 54–63%]) were higher when eCO_2 combined with the higher temperature level of 21–25 °C compared to the lower levels (Fig. 5). Due to lack of data, the interaction of temperature higher than 25 °C with eCO_2 was not evaluated in the present study.

Genotypic variation

Barley genotypes had a significantly different response of yield components to eCO_2 (Table 2 and Fig. 6). Comparing 13 genotypes on the response of aboveground biomass, the highest increase by 47.1% [CI: 43–51%] was observed for genotype "*Anakin*", while the lowest was observed for *"Harrington"* (2.7% [CI: -1–6%]) under eCO_2 (Fig. 6). The grain yield response was only available for 6 genotypes, out of them "*Alexis*" showed the highest grain yield by 38.1% [CI: 32–43%], while the lowest response was observed for genotype "*Gairdner*". The response of grain number by 58.1% [CI: 32–43%] was the highest for the *"Bambina",* while harvest index response was the highest for genotype *"Golden_Promise*" under eCO_2 (29.2 [CI: 24–33%]) (Fig. 6).

CO_2 exposure methods and rooting conditions

The responses of barley yield to eCO_2 were significantly affected by the four CO_2 exposure methods except for thousand-grain weight (Table 2). The percent of aboveground biomass enhancement under eCO_2 was higher when plants were grown in GH (34.9% [CI: 30–39%]) followed by GC (29.3% [CI: 24–33%]) as shown in Fig. 7. On the other hand, the highest increase in barley grain number (41.8% [CI: 37–45%]) and grain yield (31.8% [CI: 26–37.3%]) under eCO_2 were observed for the plants grown in the GC. In contrast, barley plants that were grown under FACE had a significantly negative response of grain number, harvest index, and thousand-grain weight (Fig. 7). On the other hand, comparing yield variable response of barley plants grown in pots and on-field conditions, higher responses were observed for plants grown in pots except for harvest index.

Table 2 Relative percentage change between-group heterogeneity (QB) for eCO_2 effect size across different categorical variables

Variables	No. of studies	No. of observations	Genotype	CO_2- levels	CO_2-exposure techniques	Rooting conditions	N	Temperature
TGW	8	44	0.93 ns	4.4 ns	1.0 ns	4.5 ns	-0.8 ns	6.2 ns
HI	9	52	10.5*	3.2*	4.6**	12.1*	−0.7 ns	1.35 ns
GY	11	46	22.9**	21.2**	22.8*	21.1***	29.9***	31.6*
GN	12	40	25.7***	17.5**	23.5***	30.8***	15.9**	21.5**
AGB	17	78	22.9***	22.3***	23.5***	22.2***	30.9***	27.3***

TGW: thousand-grain weight; HI: harvest index; GN: grain number; GY: grain yield; and AGB: aboveground biomass. Significance level: P < 0.001 (***), P < 0.01 (**), P < 0.05 (*) and not-significant (ns)

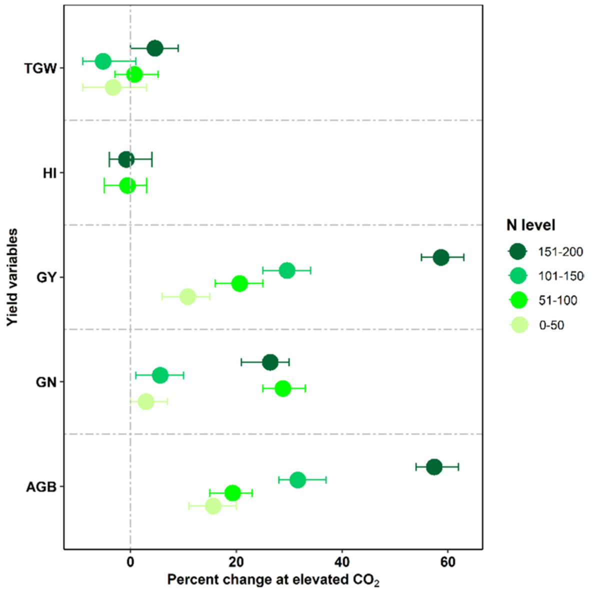

Fig. 4 Relative percentage change in barley yield response to eCO_2 under four different N fertilization treatments. The four levels of N were 0–50, 51–100, 101–150, 151–200 kg ha^{-1} analyzed out of 34 observations on the interaction between eCO_2 and N. Due to lack of data the response of harvest index to eCO_2 under N levels 0–50 and 101–150 kg ha^{-1} was not evaluated. The symbols represent the percentage change (±95% CI) in eCO_2 response relative to the corresponding control. TGW: thousand-grain weight; HI: harvest index; GY: grain yield; GN: grain number; AGB: aboveground biomass

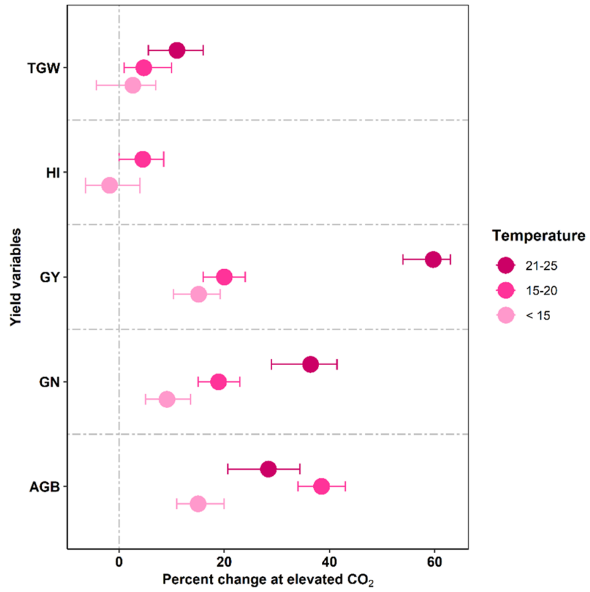

Fig. 5 Relative percentage change in barley yield response to eCO_2 under four different temperature treatments. The three temperature levels were < 15, 15–20, and 21–25 °C out of 18 observations. Temperature > 25 °C were not evaluated due to a lack of data. The symbols represent the percentage change (±95% CI) in eCO_2 response relative to the corresponding control. TGW: thousand-grain weight; HI: harvest index; GY: grain yield; GN: grain number; AGB: aboveground biomass

Higher responses of aboveground biomass (29.8% [CI: 25–34%]), grain number (38.3% [CI: 35–42%]), and grain yield (25.3% [CI: 21.1–29.2%]) under eCO_2 were obtained for the plants grown in pots. However, the response of harvest index of barley was significantly higher for plants grown on field conditions compared to pot-grown plants (Table 2 and Fig. 8).

Discussion

Responses of barley yield to eCO_2 and the interaction with N and temperature

A meta-analysis technique was used to quantitatively review and synthesize the literature on barley yield as a function of eCO_2, and its interaction with temperature, and N fertilizer treatments. The rise in atmospheric CO_2 causes mostly an increase of the total biomass of C3 plants such as barley, by stimulating net photosynthesis and reducing photorespiration (Drake et al. 1997; Mitterbauer et al. 2017; Schapendonk et al. 2000). The average increase in aboveground biomass by 23.8% under eCO_2 in this study is in line with previous meta-analysis studies on C3 crops (Ainsworth 2008; Wang et al. 2013). Similarly, a meta-analytic study of 79 crop and wild species also documented an average enhancement of biomass by 28.2% across all species due to eCO_2 (Jablonski et al. 2002). In the present study, the aboveground biomass and grain yield showed similar patterns of increase with increasing levels of eCO_2. Plants grown under an eCO_2 level of 551–650 ppm showed the highest response in aboveground biomass compared to lower eCO_2 concentrations (450–550 ppm). In the present study, grain yield and grain number were significantly increased under eCO_2 (651–720 ppm). Consequently, harvest index response was significantly increased under the highest eCO_2 (651–720 ppm), however,

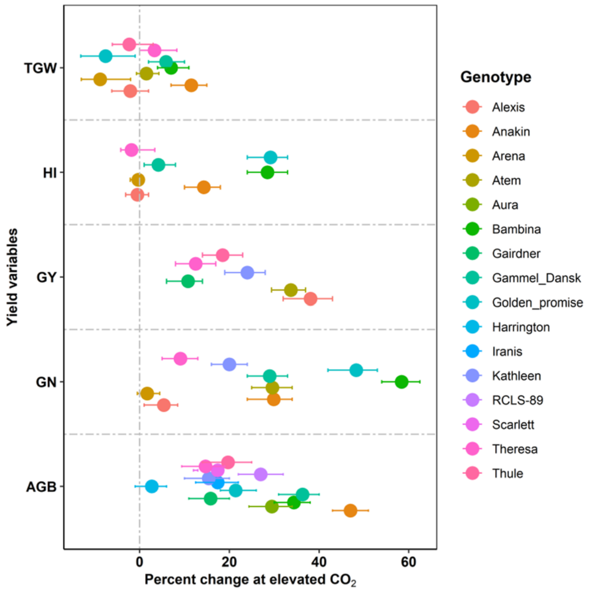

Fig. 6 Relative percentage change in yield response to eCO_2 for 16 different barley genotypes analyzed out of 84 observations. The symbols represent the percentage change (±95% CI) in response relative to the corresponding control. TGW: thousand-grain weight; HI: harvest index; GY: grain yield; GN: grain number; AGB: aboveground biomass

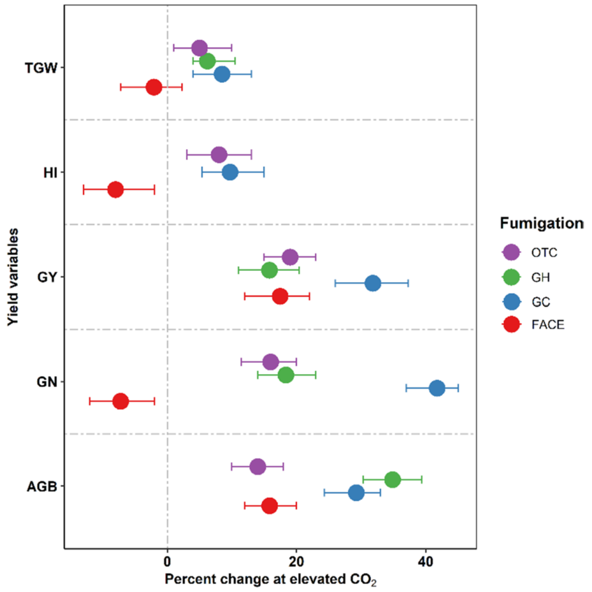

Fig. 7 Relative percentage change in barley yield response to eCO_2 under four different CO_2 exposure methods. The four exposure methods were free-air CO_2 enrichment (FACE), growth chambers (GC), greenhouses (GH), open-top chambers (OTC). The symbols represent the percentage change (±95% CI) in response relative to the corresponding control. TGW: thousand-grain weight; HI: harvest index; GY: grain yield; GN: grain number; AGB: aboveground biomass

no significant variation was observed for lower eCO_2 levels. A higher harvest index under eCO_2 implies that a relatively higher proportion of assimilated carbon is allocated to the grains. Ainsworth et al. (2002) reported a higher percentage of stimulation on aboveground biomass and grain yield at the highest eCO_2 level (600–699 ppm) in rice. Also, Kimball et al. (2001) reported an increase in the grain yield of wheat under eCO_2. The present study's findings also revealed an association with an increase in grain yield due to a larger increase in grain number rather than thousand-grain weight. As a result, the response of barley yield to eCO_2 has largely been driven by an increase in grain number. This result is similar to findings reported in other studies on C3 plants (Wilcox and Makowski 2013; Knox et al. 2016), Furthermore, increased grain yields have been linked to a higher number of tillers and grains per spike rather than an increase in the number of spikes or grain size in wheat and barley (Bourgault et al. 2013; Pleijel and Högy 2015; Amthor 2001; Wang et al. 2013). The additional carbon assimilates produced by eCO_2 levels may ensure the development of flowers and grains (Deng and Woodward 1998). However, the effect of eCO_2 on individual grain weight varied, with increases (Van Oijen et al. 1999; Li et al. 2001), decreases (Rawson 1995; Batts et al. 1997; Van Oijen et al. 1999; Heagle et al. 2000), and no change (Heagle et al. 2000; Pleijel et al. 2000).

The CO_2-derived "fertilization" effect may differ/may be different under different growth conditions such as nitrogen and temperature levels (Aranjuelo et al. 2011). It has been shown that the eCO_2 effect on total biomass and grain yield of barley decreases if the N availability is reduced (Wang et al. 2015). In line with a previous meta-analysis study on rice (Wang et al. 2015), we observed a reduction of grain yield response to eCO_2 under limited N fertilizer (0–50 kg ha^{-1}). In the present study, the highest CO_2-induced increase of aboveground biomass and grain yield was observed under the higher N level (151–200 kg ha^{-1}). In comparison, the response grain number showed a larger response to eCO_2 with 101–150 kg ha^{-1} N. In addition, the percentage increase in grain yield at eCO_2 with a combination of higher N level was related to the percentage increase

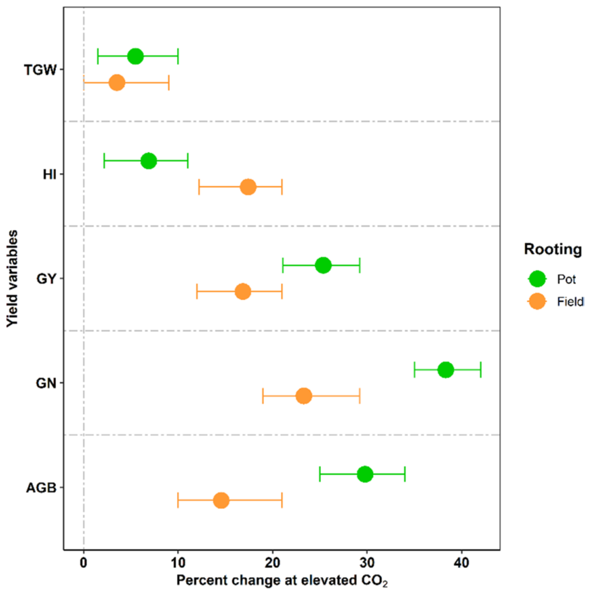

Fig. 8 Relative percentage change in barley yield response to eCO_2 under two different rooting conditions (field-grown and pot-grown). The symbols represent the percentage changes (±95% CI) in response relative to the corresponding controls. TGW: thousand-grain weight; HI: harvest index; GY: grain yield; GN: grain number; AGB: aboveground biomass

in grain number, demonstrating a positive relationship. Low N fertilization limited N concentration in vegetative plant parts, limiting any increase in grain number and, consequently, grain yield response to eCO_2 is reduced (Kim et al. 2003). Limitation in N fertilizer may also cause more pronounced acclimation of photosynthesis to eCO_2, which can limit total biomass increases at eCO_2 (Suter et al. 2001; Ainsworth et al. 2003). Because eCO_2 has a significant effect on crop N uptake and concentration in biomass, crop production's response to elevated CO_2 is highly dependent on the availability of nutrient resources (Leakey et al. 2012). In our meta-analysis, low N input constrained barley yield in response to eCO_2 as compared to high N input. This decrease is most likely due to the direct relationship between N availability and growth parameters such as grain number throughout the growing season (Mitchell et al. 1993; Kim et al. 2001, 2003).

On the other hand, the temperature is also one of the most determinant factors of crops development rates and yield (Wang et al. 2015). Higher temperatures result in accelerated crop development, and thus a shorter growing period, resulting in lower grain yield (Hatfield and Prueger 2015). We found a significant interaction between eCO_2 and temperature on barley yield variables. In comparison, better enhancement of aboveground biomass was observed under the combination of eCO_2 and temperature level (15–20 °C). Moreover, grain yield and grain number were also increased under the interaction of eCO_2 and temperature level (21–25 °C)), which disagrees with previous studies (Wang et al. 2015; Hatfield and Prueger 2015). Due to lack of data, the interactive effect of eCO_2 with a temperature higher than 25 °C is missing in the present study. Nevertheless, the significantly higher number of grains observed in the present study might be responsible for higher grain yield under the combination of eCO_2 and higher temperature (21–25 °C). In contrast to our study, Wang et al. (2015) reported that under eCO_2 an increase of temperature by 1 °C may lead to a decrease in rice yield by 9.4% at temperature levels of 24–26 °C. In addition, Amthor (2001) reviewed the effects of eCO_2 on wheat and found that increasing temperatures by 5 °C from the ambient level (12.7 °C) may offset the positive effects of eCO_2. However, he mentioned also that eCO_2 can counteract the negative effects of higher temperatures, which may partially explain the increase in grain yield and grain number due to eCO_2 in combination with higher temperature levels in the present study.

Variation in the response of barley yield to eCO_2

Genotypic variation

The identification of consistent genotypic variability in the response to eCO_2 is a prerequisite to using this information in breeding programs. Barley yield variable responses to eCO_2 were different among barley genotypes, which might be related to the varietal character of genotypes. In the present study modern spring barley genotype "*Anakin*" had more aboveground biomass under eCO_2, followed by the old landrace *"Gammel_Dansk"*, *"Bambina"* and *"Aura"*, while *"Iranis"* showed the lowest response. The genotype "*Bambina*", a mid-maturing spring cultivar, had the highest grain number followed by early maturing and high yielding genotype *"Golden Promise"* at eCO_2. However, grain yield and harvest index response were higher for *"Alexis",* a heat-tolerant, two-rowed German genotype, and *"Atem"*, a drought-tolerant European modern spring genotype. Genetic variability on the response of total biomass and grain yield to eCO_2 was reported in previous studies on wheat (Ziska et al. 2004) and rice (Wang et al. 2015). Modern genotypes do not necessarily always perform better than old ones at higher CO_2 levels. For example, the aboveground biomass of an older wheat genotype can increase more than that of a modern genotype in response to increasing CO_2 (Hay and Gilbert 2001). In contrast to the present findings, previous studies in soybean (Bishop et al. 2015) and common bean (Bunce 2008) could not detect differences between the cultivars tested in their response to eCO_2 for grain yield and other yield variables evaluated. The response of thousand-grain weight to eCO_2 did not differ among the barley genotypes in the present study. However, previous studies have found a variety of genotypes response of thousand-grain weight under eCO_2 (Weigel et al. 1994). The findings from the present meta-analysis suggest breeding for the exploitation of eCO_2 might enhance future crop production. Previous studies have suggested that there is very little evidence that breeders have inadvertently selected for increased CO_2 responsiveness, and indeed several studies have suggested the opposite, that older genotypes are more responsive to eCO_2 than modern genotypes (Ainsworth et al. 2008; Leakey and Lau 2012; Ziska et al. 2012).

Experimental conditions

The estimation of the response of barley yield to eCO_2 can be significantly affected by CO_2 exposure methods. Previous studies reported an enhancement of aboveground biomass and grain yield at eCO_2 is lower under FACE experiments than other enclosure methods (Long et al. 2006; Tubiello et al. 2007). In addition, a meta-analysis study by Broberg et al. (2019) recorded a higher wheat yield for plants grown in OTCs than with FACE. The present meta-analysis shows that plants grown in GC had relatively higher aboveground biomass and grain yield due to eCO_2 than those plants grown under FACE or OTC, which is in line with an earlier study (Long et al. 2006). Similarly, when plants were grown in GC, higher grain yield due to eCO_2 has been reported in meta-analyses of rice (Wang et al. 2015) and wheat (Wang et al. 2013). The findings from the present meta-analysis and previous studies showed that the rapid fluctuation of CO_2 concentration has lowered plant photosynthesis in FACE experiments, which resulted in a lower accumulation of biomass and grain yield (Holtum and Winter, 2003). However, another meta-analysis of wheat noted no significant difference between FACE and OTC experiments concerning the response of grain yield to eCO_2 (Feng et al. 2008). Nonetheless, no study seems to have directly compared the response of barley yield variables to different CO_2 exposure methods of the same genotype grown under identical soil, environmental condition, and cultivation practice.

The effect of growth conditions on the response of barley yield to eCO_2 varies between yield variables (Wang et al. 2015; Broberg et al. 2019). In the present study, the response of aboveground biomass, grain number, and grain yield were significantly higher for pot-grown barley rather than under field grown. This disagrees with the hypothesis that restricted root growth in pot experiments leads to a down-regulation of photosynthesis and consequently diminishes the response of plants to eCO_2 (Arp 1991; Curtis and Wang 1998). In the present meta-analysis, the restricted rooting volume for pot-grown plants did not have a major impact on the eCO_2 stimulation of aboveground biomass and the number of grains in barley. One possible reason for the apparent discrepancy may be that all the results from pot-grown plants in the present meta-analysis derived from GC studies, which showed much larger responses to eCO_2 than FACE conditions. In agreement with our findings, previous meta-analyses have also reported higher aboveground biomass and grain yield responses of pot-grown wheat plants under eCO_2 as compared to field-grown plants (Taub and Wang 2008; Wang et al. 2013). In contrast, other studies have reported non-significant variation in responses of grain yield to eCO_2 for pot-grown and field-grown wheat plants (Feng et al. 2008). However, the responses of harvest index to eCO_2 were higher for field-grown plants in the present study, which disagrees with the previous study on rice (Ziska and Bunce 2000).

Conclusions

This meta-analysis quantified the effect of eCO_2 as a single factor and its interaction with N and temperature on barley production. A strong positive effect of eCO_2 was observed for aboveground biomass, grain yield, and grain number. However, the responses of aboveground biomass, grain number, and grain yield to eCO_2 were lower under limited N fertilizer (< 50 kg ha^{-1}). In general, the magnitude of the CO_2-induced effect on barley grain yield will depend on the future atmospheric CO_2 concentration and agronomic practices such as genotype choice, and growing conditions. The existence of genetic variation in barley response to eCO_2 is needed to breed barley to the future atmospheric environment. Modern barley genotype "*Anakin*" had higher aboveground biomass under eCO_2 than older ones, whereas *"Alexis"* and *"Atem"* showed higher grain yield and harvest index. Grain number was relatively higher due to eCO_2 for genotype *"Bambina"*. Uncertainties remain, however, regarding the responses to environmental conditions (temperature, N) of barley yield parameters, mainly aboveground biomass, grain number, and grain yield were significantly affected. The positive effect of eCO_2 was observed to be higher in combination with high N (150–200 kg ha^{-1}) and temperature levels (21–25 ℃). In the present meta-analysis, some other important interactions, which potentially affect crop production such as the interaction of eCO_2 with drought and O_3, were not quantified. In addition, there is a lack of data that compares the effect of different exposure methods and rooting conditions side by side on barley yield response to eCO_2. Field experiments that better characterize the responses of barley and its interaction with additional factors to eCO_2 can help reduce uncertainties due to climate change in estimating future food production. Such studies might be used for summarizing and drawing conclusions on estimating food production in the future.

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Author Contributions M.G. and P.H. conceived and designed the study; data collection was made by M.G. M.G and W.A.M participated in the analysis of the data; M.G. wrote the paper with substantial input from P.H. B.H and W.A.M.

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Data availability Data obtained for the present study is available.

Code availability Software application code is available.

Declarations

Conflict of interest The authors have no conflict of interest.

Appendix 1

Literature search strings for the meta-analysis review were used in various databases.

Scopus, Science Direct, and Google Scholar were used to search the literature using the below search strings.

"climate change" [title] [tiab] [key] AND ("barley yield" [title] OR "yield variables" [title] OR "yield components" [title] OR "elevated CO_2" [title], OR "carbon dioxide and temperature" [title] OR "carbon dioxide and nitrogen" [title] OR "elevated CO_2" [title] OR ("temperature" OR "nitrogen" AND ("aboveground biomass" OR "grain yield" OR "grain number" OR "thousand-grain weight" OR "harvest index")) [title] OR meta-analysis [title] OR "meta analysis" [title] OR "systematic review" [title] OR "systematic-review" [tiab] OR "quantitative review" [tiab]).

Appendix 2

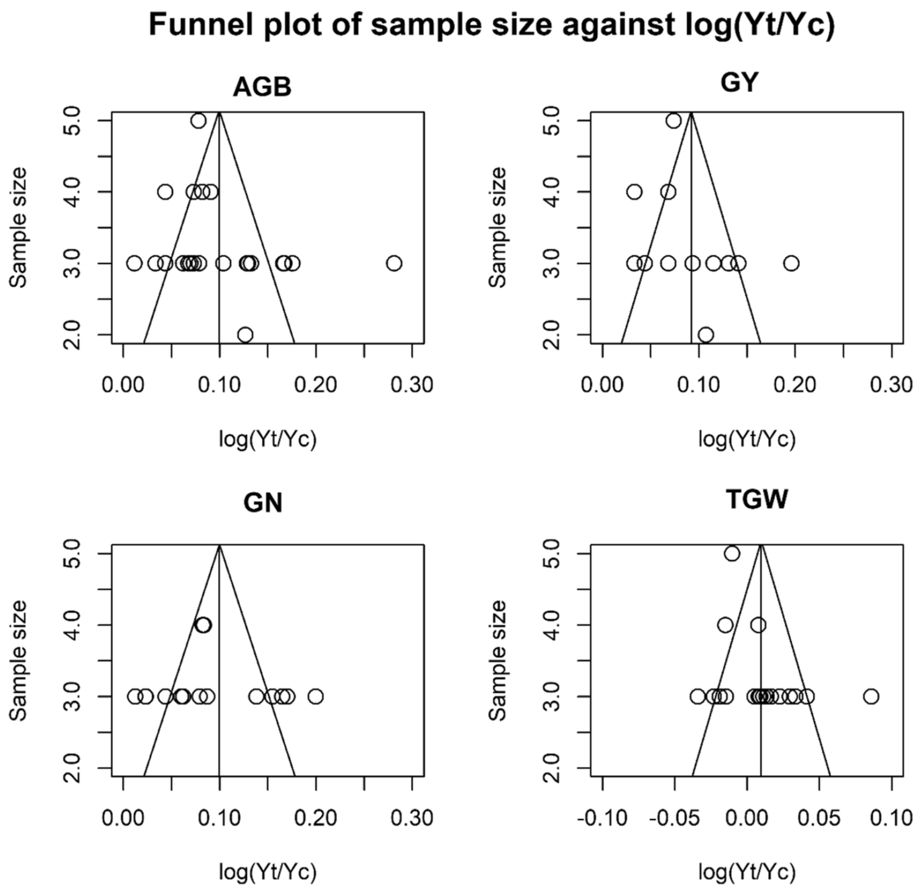

Fig. 9 Funnel plot of sample size against the log response ratio of the mean response of the experimental treatment (Yt) to the mean response of the control treatment (Yc) to identify a possible publication bias. AGB: aboveground biomass; GY: grain yield; GN: grain number and TGW: thousand-grain weight

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4. Publication II

Impacts of Carbon Dioxide Enrichment on Landrace and Released Ethiopian Barley (*Hordeum vulgare* L.) Cultivars

Gardi, M.W.; Malik, W.A.; Haussmann, B.I.G. Impacts of Carbon Dioxide Enrichment on Landrace and Released Ethiopian Barley (*Hordeum vulgare* L.) Cultivars. *Plants* 2021, 10, 2691.

The previous chapter quantified and summarized barley's response to eCO_2 as well as the interactive effect with N and temperature. In Chapter 4, the growth and yield response of a subset of Ethiopian landraces and released barley cultivars to eCO_2 were evaluated. To the best of our knowledge, no information is currently available regarding the response of Ethiopian barley cultivars to eCO_2. A climate chamber experiment with 15 landraces and 15 released cultivars was carried out at two levels of CO_2 (400 and 550 ppm). According to the analysis, CO_2 fertilization is likely to increase barley growth, yields, and water-use efficiency. In comparison, grain yield was much more sensitive to eCO_2 than vegetative biomass, owing to significant increases in ear biomass, grain number, and harvest index. In future climate conditions, the water-use efficiency of vegetative biomass and grains was improved. Grain yield gain was associated with a high grain number and grain water-use efficiency per plant. CO_2 fertilization benefited released cultivars more than landraces on average. However, there was a wide range of intraspecific variations in the responses of biomass and grain yield parameters across both the landrace and released cultivars. The study on the interaction between cultivars and the environment may contribute to a better understanding of the performance thresholds for cultivars under climate change conditions. Grain yield production may benefit from the identification of cultivars with higher grain numbers and more efficient water use in grain under future climate conditions. Food security, on the other hand, entails more than just production. Further investigation of the nutritional quality of barley cultivars under eCO_2 conditions is required. Furthermore, the growth and stress tolerance values of Ethiopian barley cultivars in response to the interactive effects of eCO_2 conditions, warming, and drought should be investigated to improve germplasm resource utilization under changing climatic conditions.

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Impacts of Carbon Dioxide Enrichment on Landrace and Released Ethiopian Barley (*Hordeum vulgare* L.) Cultivars

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Abstract: Barley (*Hordeum vulgare* L.) is an important food security crop due to its high-stress tolerance. This study explored the effects of CO_2 enrichment (eCO_2) on the growth, yield, and water-use efficiency of Ethiopian barley cultivars (15 landraces, 15 released). Cultivars were grown under two levels of CO_2 concentration (400 and 550 ppm) in climate chambers, and each level was replicated three times. A significant positive effect of eCO_2 enrichment was observed on plant height by 9.5 and 6.7%, vegetative biomass by 7.6 and 9.4%, and grain yield by 34.1 and 40.6% in landraces and released cultivars, respectively. The observed increment of grain yield mainly resulted from the significant positive effect of eCO_2 on grain number per plant. The water-use efficiency of vegetative biomass and grain yield significantly increased by 7.9 and 33.3% in landraces, with 9.5 and 42.9% improvement in released cultivars, respectively. Pearson's correlation analysis revealed positive relationships between grain yield and grain number ($r = 0.95$), harvest index ($r = 0.86$), and ear biomass ($r = 0.85$). The response of barley to eCO_2 was cultivar dependent, i.e., the highest grain yield response to eCO_2 was observed for *Lan_15* (122.3%) and *Rel_10* (140.2%). However, *Lan_13*, *Land_14*, and *Rel_3* showed reduced grain yield by 16, 25, and 42%, respectively, in response to eCO_2 enrichment. While the released cultivars benefited more from higher levels of CO_2 in relative terms, some landraces displayed better actual values. Under future climate conditions, i.e., future CO_2 concentrations, grain yield production could benefit from the promotion of landrace and released cultivars with higher grain numbers and higher levels of water-use efficiency of the grain. The superior cultivars that were identified in the present study represent valuable genetic resources for future barley breeding.

Keywords: barley; biomass; CO_2 enrichment; *Hordeum vulgare* L.; water-use efficiency; yield

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1. Introduction

The global demand for food crops is increasing and may continue to do so for decades. A 70–100% increase in the cereal food supply by 2050 is required to feed the predicted world population of over nine billion people [1]. In terms of production and consumption, barley (*Hordeum vulgare* L.) is one of the most important cereal crops in the world following wheat, maize, and rice. It is cultivated both in highly productive agricultural systems and at the subsistence level in marginal environments [2]. Ethiopia is the second-largest barley producer in Africa, accounting for nearly 25% of the total production [3]. It has been cultivated in Ethiopia for the last 5000 years and accounts for 8% of the total cereal production in the country [4]. In the 2017/18 growing season, the national area coverage was 975,300 ha, with the production and productivity values of barley being approximately 2.1 million tons and 2.17 tons ha^{-1}, respectively [3]. It is grown at elevations from 1500 to over 3500 m above sea level (m.a.s.l) and is predominantly cultivated between 2000 and 3000 m.a.s.l. [5,6].

Ethiopian barley germplasm has been used internationally as a source of useful genes due to its improved traits, including improved protein quality and disease and drought tolerance [5,7]. Long-term geographic isolation and adaptation to diverse climatic conditions and soil types resulted in a high level of variation between cultivars [8]. The crop is primarily used as a type of food and beverage in more than 20 different ways, which reflects its cultural and nutritional importance [9]. Despite its importance and morphological variations, one key challenge in barley breeding is the issue of developing cultivars that can face the challenges of changing climatic conditions [10]. Changes in the global atmospheric CO_2 concentration constitute one of the most important and well-known examples of global climate change. The current increase in CO_2 will likely continue into future decades and may bring the concentration close to 550 ppm by 2050 [11,12]. Elevated CO_2 (eCO_2) levels are known to have positive effects on photosynthetic processes, and consequently, on plant growth in C3 plant species, mainly through the modification of water and nutrient turnover [13–15]. Thus, as CO_2 is fundamental for plant production, understanding cultivar behavior and the targeted exploitation of this resource via plant breeding could optimize yields and contribute to future food security [16–18].

Several CO_2-enrichment studies regarding major cereal species, i.e., barley [19–21], wheat [22,23], and rice [24], reported substantial intraspecific variation between cultivars regarding plant growth and yield in response to eCO_2 enrichment. In contrast, another study regarding different cultivars of wheat reported non-significant intraspecific variation in yield responses [25]. To the best of our knowledge, no information is currently available regarding the response of Ethiopian barley cultivars to eCO_2. Therefore, the present study aimed to evaluate the growth, yield formation, and water-use efficiency response of Ethiopian barley cultivars under current and future CO_2 concentrations.

2. Results

2.1. Plant Height and Biomass Allocation Pattern

Significant impacts caused by CO_2 enrichment were observed for several yield variables in both the landrace and released cultivars, except in the variables of leaf biomass fraction, the number of ears per plant, and thousand-grain weight. The interaction between CO_2 and the cultivars also had a significant effect on most of the yield variables (Table 1). The average plant height of the landrace and released cultivars in the ambient CO_2 (aCO_2) condition were 101.9 and 94.5 cm, respectively (Table 1). The effect of CO_2 enrichment was observed in the variable of plant height, with an increase of 7.6% in landraces and 6.7% in released cultivars (Figure 1). The average vegetative biomass of the landrace was 35.6 g dry weight per plant in the aCO_2 condition (Table 1), while the released cultivars had 39.4 g dry weight per plant (Table 1). Significant increases in vegetative biomass, by 7.6 and 9.4%, respectively, were recorded across the landrace and released cultivars in the eCO_2 condition (Figure 1). The increase observed in vegetative biomass was mainly due to the significant effect of eCO_2 on the stem biomass in both the landrace and released cultivars (Table 1). As shown in Figure 2, a negative correlation between vegetative biomass and grain yield ($r = -0.51$, $p < 0.05$) as well as harvest index ($r = -0.85$, $p < 0.001$) was observed.

Table 1. Analysis of variance results. Mean and standard error (S.E.) of phenological parameters of landrace (Gen) and released cultivars (Cul) under ambient and elevated CO_2 conditions, as well as their interactions.

Variables	Cultivar	aCO_2	eCO_2	S.E.	Δ %	CO_2	Gen/Cul	CO_2 ×Gen/Cul
Plant height (cm)	Landrace	101.9	109.6	3.8	7.6	***	*	*
	Released	94.5	100.8	3.8	6.7	***	***	ns
Vegetative biomass (g plant^{-1})	Landrace	35.6	38.3	2.0	7.6	***	***	***

	Released	39.4	43.1	2.0	9.4	***	***	***
Stem biomass (g plant^{-1})	Landrace	19.3	21.4	1.4	10.9	***	***	***
	Released	21.5	23.7	1.3	10.2	***	***	***
Leaf biomass (g plant^{-1})	Landrace	11.2	11.4	0.7	1.8	ns	***	***
	Released	12.6	13.3	0.7	5.6	***	**	*
Ear biomass (g plant^{-1})	Landrace	13.2	16.5	1.8	25.0	***	***	ns
	Released	11.9	15.6	1.8	31.1	***	**	ns
Chaff (awn) biomass (g plant^{-1})	Landrace	5.1	5.5	1.6	9.0	**	***	***
	Released	5.2	6.1	1.2	17.6	***	***	***
Number of ears (plant^{-1})	Landrace	13.8	15.2	1.8	10.2	ns	**	ns
	Released	12.8	13.4	2.2	4.7	ns	*	ns
Number of grain (plant^{-1})	Landrace	146.0	193.0	30.9	32.2	***	***	***
	Released	134.0	176.0	34.2	31.3	***	***	ns
Grain yield (g plant^{-1})	Landrace	8.1	10.9	1.7	34.1	***	***	***
	Released	6.7	9.42	1.7	40.6	***	***	**
Thousand-grain weight (g)	Landrace	54.5	56.2	3.1	3.1	ns	***	ns
	Released	49.2	54.3	5.6	10.4	*	**	ns
Harvest index	Landrace	0.21	0.24	0.03	14.3	**	***	ns
	Released	0.16	0.20	0.03	23.3	***	***	***
Total water use (WU_T, L plant^{-1})	Landrace	9.2	9.1	0.1	−1.1	*	***	***
	Released	9.3	9.3	0.1	0.0	ns	***	***
Water-use efficiency of vegetative biomass (WUE_B, g L^{-1})	Landrace	3.8	4.1	0.1	7.9	***	***	***
	Released	4.2	4.6	0.1	9.5	***	***	***
Water-use efficiency of grains (WUE_G, g L^{-1})	Landrace	0.9	1.2	0.1	33.3	***	***	ns
	Released	0.7	1.0	0.1	42.9	***	***	ns

Significance level: $p < 0.001$ (***); $p < 0.01$ (**); $p < 0.05$ (*); and non-significant (ns).

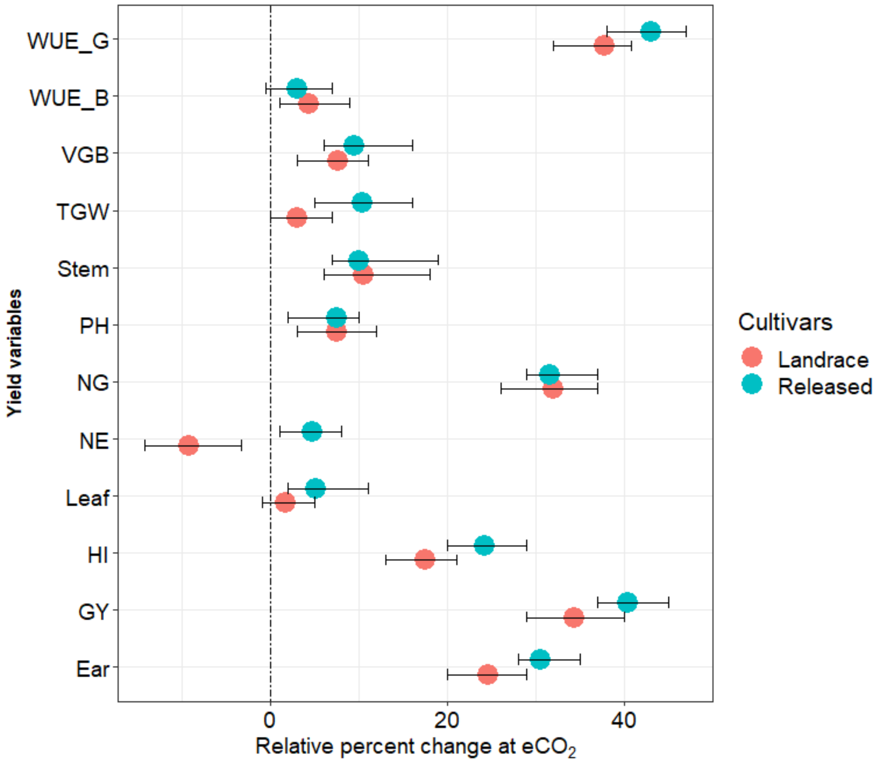

Figure 1. Relative effect of eCO_2 condition on plant height, biomass fractions, yield components, and water-use efficiency of barley. Average relative changes due to CO_2 enrichment against aCO_2 are presented, with error bars representing their standard errors. Ear: ear biomass; GY: grain weight; HI: harvest index; Leaf: leaf biomass; NE: number of ears; NG: grain number; PH: plant height; Stem: stem biomass; TGW: thousand-grain weight; VGB: vegetative biomass; WUE_B: water-use efficiency of vegetative biomass; and WUE_G: water-use efficiency of grain.

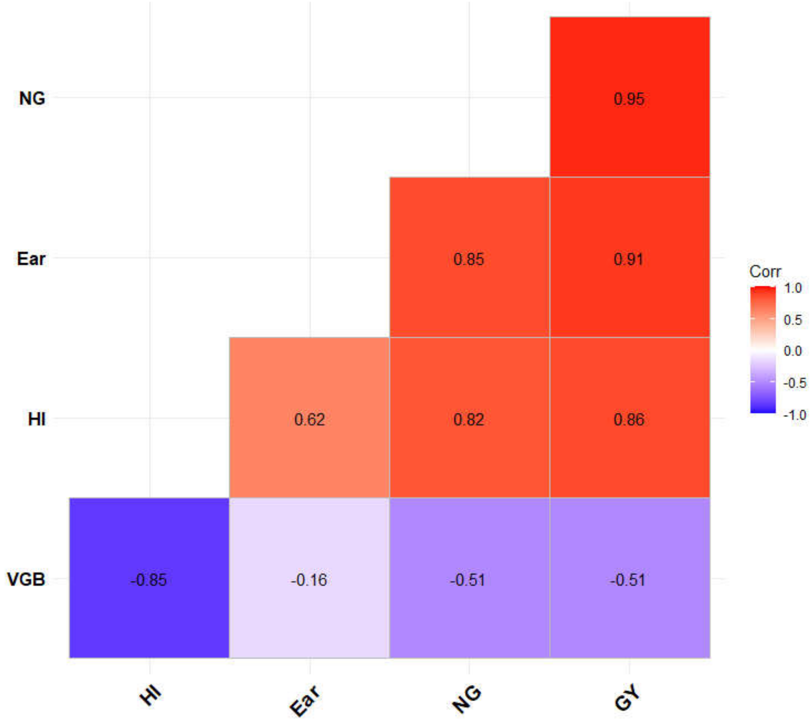

Figure 2. Correlation between grain yield, yield parameters, and water-use efficiency. VGB: vegetative biomass; Ear: ear biomass; NG: number of grains; GY: grain yield; WUE_G: water-use efficiency of grains; HI: harvest index. The value shows Pearson's correlation coefficient. The minus sign indicates a negative correlation between the variables.

2.2. Grain Yield Parameters

Grain yield and its parameters were significantly affected by genotype/cultivars, CO_2 treatment, and their interaction in both the landrace and released cultivars (Table 1). The average grain yield of the landrace was 8.1 g dry weight per plant, resulting from 13.8 ears and 146 grains per plant. On the other hand, the released cultivars had a grain yield of 6.7 g dry weight per plant from 12.8 ears and 134 grains per plant, on average, under the aCO_2 conditions. Increases in the grain yield of the landrace and released cultivars, by 34.1 and 40.6%, respectively, were recorded under the eCO_2 condition (Table 1 and Figure 1). All yield components contributed significantly to the increase in grain yield, except for the number of ears. The number of grains per plant showed the largest increase of 32.2% in the landrace and 31.3% in the released cultivars (Table 1 and Figure 1). In accordance with this, the harvest index increased by 14.3% (landraces) and 23.3% (released cultivars) in the eCO_2 condition. The eCO_2 condition was recorded to have a significant effect on thousand-grain weight for the released cultivars; the thousand-grain weight increased by 10.4% on average, while the change was not significant in the landrace (Figure 1).

In Figure 2, the correlation analysis revealed that grain yield had a positive and strong association with the number of grains ($r = 0.95$, $p < 0.001$), ear biomass ($r = 0.91$, $p < 0.001$) and harvest index ($r = 0.86$, $p < 0.001$). In addition, the performance of the genotypes/cultivars regarding the response of grain yield under the aCO_2 condition versus the eCO_2 condition had a significant and positive correlation in the landrace ($r = 0.64$, $p = 0.01$) and released cultivars ($r = 0.93$, $p < 0.001$), as shown in Figure 3. Among the landrace cultivars, *Lan_15* displayed the highest yield, while *Lan_7* displayed the lowest yield under both the ambient and elevated CO_2 conditions. Comparing the released cultivars, the highest grain yield was recorded for *Rel_4*, and *Rel_10* had the lowest yield. Moreover, a strong and positive correlation of cultivars was recorded for grain number per plant under the aCO_2 condition versus the eCO_2 condition (Figure 3); however, the best genotypes under aCO_2 were not always the best genotypes under eCO_2 in terms of both number of grains and grain yield.

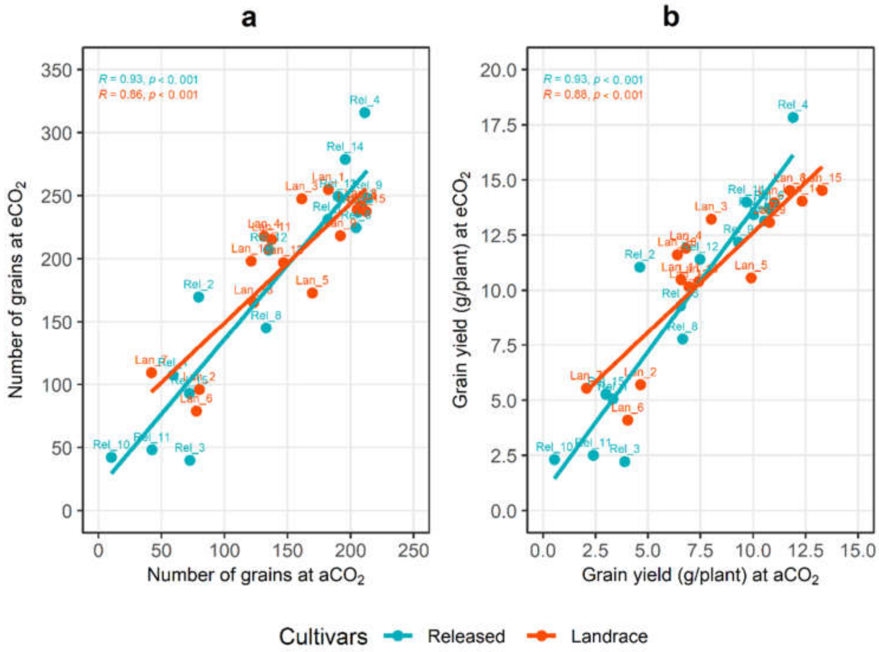

Figure 3. Mean response of landrace and released cultivars under elevated (500 ppm) CO_2 plotted against mean response under ambient (400 ppm) CO_2, where responses refer to (**a**) number of grains per plant and (**b**) grain yield (in grams) per plant.

2.3. Water-Use Efficiency

The variables of water-use efficiency of vegetative biomass (WUE_B) and grain (WUE_G) were significantly affected by the CO_2 condition and type of cultivar ($p < 0.001$), as shown in Table 1. However, their interaction did not affect the response of total water use in both the landrace and released cultivars. In the aCO_2 condition, the landrace cultivar used 9.2 L plant^{-1} of WU_T, and had 4.7 g L^{-1}, WUE_B, and 0.9 g L^{-1} WUE_G (Table 1). On the other hand, the released cultivars used 9.3 L plant^{-1} of WU_T and had 4.9 g L^{-1} WUE_B, and 0.7 g L^{-1} WUE_G (Table 1). The levels of total water consumption of water by the landrace and released cultivars were not significantly different under the different CO_2 levels. The effect of CO_2 enrichment was higher in the response of WUE_G than WUE_B. WUE_G was increased by 33.3% in landraces and 42.9% in the released cultivars (Table 1 and Figure 1). In comparison, *Lan_15* and *Rel_4* showed the highest WUE_G among the landrace and released cultivars, respectively, while the lowest WUE_G was observed in *Lan_6*, *Lan_7,* and *Rel_10* (Figure 4a,b).

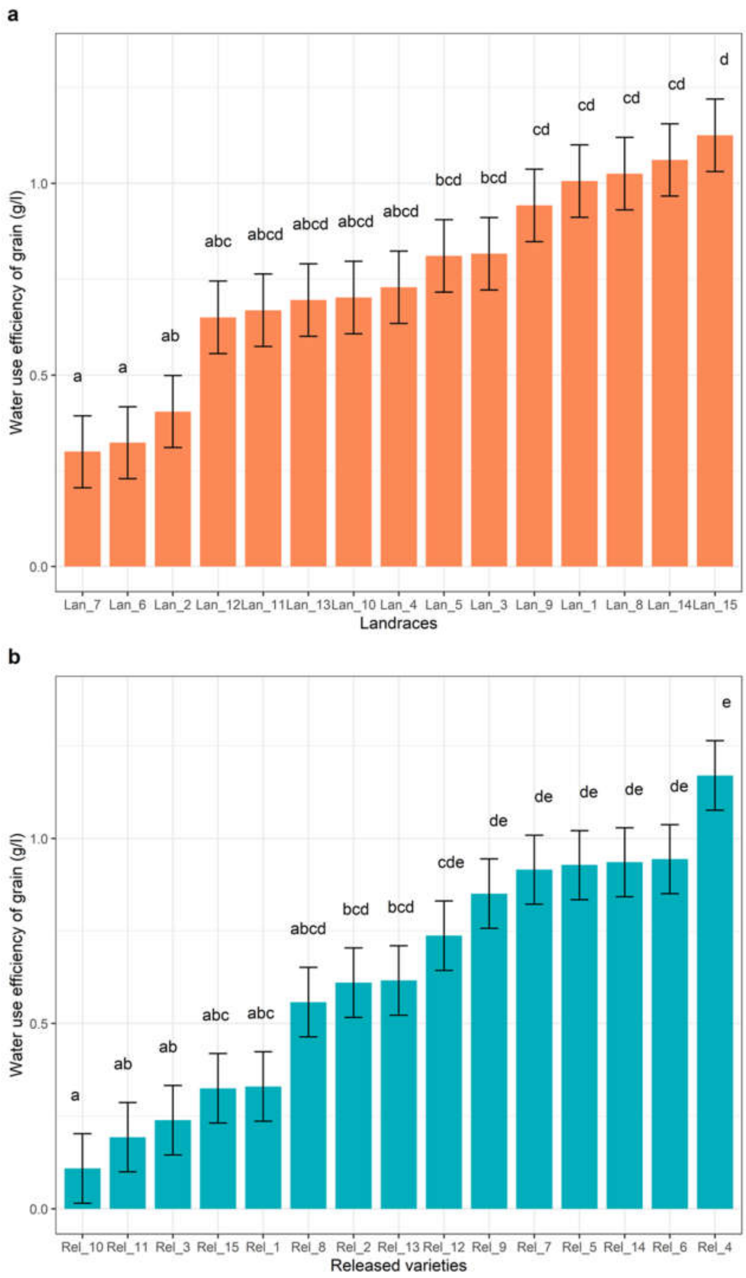

Figure 4. Mean response of landrace (**a**) and released cultivars (**b**) regarding the water-use efficiency of grains (WUE_G, g L^{-1}). The letters indicate the significant level between genotypes/cultivars. Mean values sharing a letter are not significantly different.

3. Discussion

3.1. The Overall Effect of eCO_2 *on Vegetative Biomass, Grain Yield, and Water-Use Efficency*

Atmospheric CO_2 enrichment is expected to contribute to the required increase in grain yield production in the future [15,26,27]. Our findings from the climate chamber experiment, where the eCO_2 condition was applied as a single factor, correspond well with findings in previously published data. In the present study, on average, vegetative biomass was increased by 7.6% in landraces and 9.4% in the released cultivars, respectively. The enhancement was predominantly due to higher biomass allocation towards ear and stem biomass. The eCO_2 condition was observed to have a significant effect on the response of leaf biomass in the released cultivars alone. In line with the present results, findings from CO_2 enrichment studies regarding barley reported the significant enhancement of vegetative biomass due to higher CO_2 concentrations [28–30]. A previous study [15] summarized the biomass response of the C3 species and reported an average enhancement of vegetative biomass by 16% under eCO_2 conditions. Comparable results were also reported regarding other C3 crops, such as wheat [31] and rice [26].

In the present study, the released cultivars had a higher relative grain yield increase (40.6%) under the eCO_2 condition as compared to the landraces (34.1%). This supports the hypothesis that enhanced net-photosynthesis in eCO_2 conditions was unconsciously targeted through breeding. However, surprisingly, the landrace group had higher actual grain yield production levels under both the aCO_2 and eCO_2 conditions. In support of this finding [28], grain yield was determined via grain number per plant and ear biomass, which indicates that CO_2 enrichment and the acquisition of extra carbon were carried forward to the grains rather than the biomass yield. Previous studies regarding barley [19,20] and wheat [32,33] reported the positive correlation of grain yield with grain number. In the current study, an average enhancement of thousand-grain weight by 10.4% due to eCO_2 conditions was recorded in the released cultivars, whereas the response was not significantly affected in the landraces. In line with our findings, a study regarding wheat reported an enhancement of thousand-grain weight by 3.8–7.0% [34]; on the other hand, a non-significant effect of eCO_2 conditions on the thousand-grain weight of barley and wheat was reported in other studies [20,35]. The effects of eCO_2 conditions on the harvest index have been reviewed in rice, wheat, and soybean, with contradictory results. In the present study, the harvest index was increased by 23.3 and 14.3% in the released and landrace cultivars, respectively, under the eCO_2 condition. Similarly, in [27], a significant increase in the harvest index was also displayed in rice under eCO_2 conditions, which was contrary to a decrease in harvest indexes related to soybean and wheat [26,36]. The actual grain yield of landrace observed in the present study was higher compared to that of the released cultivars; however, the positive effect of eCO_2 was greater in the released cultivars. Accordingly, the relative percentage change of the harvest index was observed to be higher for the released cultivars compared to the landraces. Our finding supports the effort of breeding to reduce the percentage of vegetative biomass to increase the harvest index of crops, which is in line with the findings of [17].

As CO_2 levels rise above the current ambient level, photosynthesis is commonly enhanced and transpiration is frequently reduced, resulting in greater water efficiency and increased plant growth and productivity [37]. In the present study, a significant improvement regarding WUE_G was displayed. Average enhancements in the values of WUE_G by 33.3 and 42.9% were observed in the landrace and released cultivars, respectively, under the eCO_2 condition. In agreement with these findings, previous studies reported that eCO_2 conditions had a significant effect on the WUE_G and WUE_B values of barley and other crops. For instance, a study regarding two barley cultivars reported a significant enhancement of water-use efficiency of vegetative biomass and grain under well-watered conditions [17]. Furthermore, increases in WUE values by 20% under well-watered and by 42% under drought conditions, due to the presence of eCO_2, were reported [29]. Regarding wheat, the authors of [38,39] reported a significant enhancement of WUE_B and WUE_G values due to high eCO_2 conditions. On the other hand, the author of [40] revealed a clear reduction in the water consumption of barley under eCO_2 conditions. The current study, as well as several previous studies, revealed that eCO_2 conditions cause increases in water-use efficiency values by increasing growth and yield more so than by increasing water consumption. This would be beneficial for use in future food production, especially in water-limited areas.

3.2. Cultivar Specific Responses to eCO_2 on Barley Production

In this study, a wide range of intraspecific variation was observed in the responses of the measured yield parameters to the eCO_2 condition, from negative to large increments. The response of grain yield to the eCO_2 condition ranged from −25% (*Lan_14*) to +122.3% (*Lan_15)* in the landraces, while the released cultivars showed a 42% reduction in grain yield (*Rel_3*) to an increment of 140.2% (*Rel_10*) under the eCO_2 condition. High grain yield and stability were found among landraces and the released cultivars. The landraces originated and were grown in different altitudes, indicating that suitable resources for climate resilience are available from different areas. The highest yielding landraces were *Lan_15*, *Lan_8*, *Lan_1*, *Lan_9,* and *Lan_6* under both the aCO_2 and eCO_2 conditions. The highest yielding landraces were grown in various parts of Ethiopia between 1642 and 3570 m.a.s.l, indicating the diversity and potential of choosing cultivars for future climate conditions. On the other hand, the highest yielding released cultivars were *Rel_4*, *Rel_5*, *Rel_6*, *Rel_7,* and *Rel_10*, which were characterized by early maturation, high yields, and resistance to lodging and leaf diseases (*Pyrenophora teres* and *Rhynchosporium secalis*). As shown in our findings, CO_2 enrichment studies regarding different barley cultivars reported a significant variation among cultivars in the response of grain yield and its parameters [20,21,41]. The greater enhancement of ear biomass per plant and improvement regarding WUE_G values significantly contributed to the observed grain yield gain in the highest yielding cultivars. In line with these findings, several studies have reported that barley yield responses to eCO_2 conditions are mostly cultivar dependent [19,23,42]. Studies involving other C3 crops have also reported significant differences between cultivars tested in future climate change scenarios. Variations in the responses to eCO_2 conditions in rice cultivars, for example, have been recorded, ranging from a 31% yield reduction to a 41% yield gain [24,43]. Similarly, significant variation in yield response under eCO_2 conditions, ranging from 20 to 80%, was observed in soybean cultivars [44]. Further variations in yield response were observed in other studies, with yield gains of between 31 and 41% being found [24,43]. As has been seen in previous studies, in the present study, negative growth effects of eCO_2 were observed regarding vegetative biomass and grain yield. The negative yield responses may partly be associated with alterations in the shoot: root carbon allocation between the cultivars examined. Previous studies reported positive root growth effects in barley via eCO_2 conditions [45,46]. Cultivars with negative vegetative biomass accumulation under eCO_2 were allotted newly assimilated carbon, but this would preferentially take place below the ground level for the enhanced development of their root systems at the expense of the vegetative biomass [21]. A review of different experiments conducted under eCO_2 conditions listed 13 C3-plant species that exhibited reductions in vegetative biomass by up to 42% [47]. A set of more than 100 spring barley cultivars grown under eCO_2 conditions yielded negative responses comparable to the current findings [48]. In general, studies on C3 crops indicate that intraspecific yield variations under eCO_2 conditions are primarily related to changes in carbon allocation within cultivars, rather than physiological traits related to carbon assimilation [45,46]. The current study, as well as other similar studies, have found a wide range of eCO_2 responsiveness in some of the world's most important food crops, implying that selecting for eCO_2 responsiveness may ensure long-term productivity under eCO_2 conditions [18,26,49,50]. The *Lan_15*, *Lan_8*, *Lan_1*, *Lan_9*, and *Lan_6* variants among the landraces and the *Rel_4*, *Rel_5*, *Rel_6*, *Rel_7*, and *Rel_10* variants among the released cultivars are the top five highest-yielding variants due to improved grain number values under the eCO_2 condition. They represent important genetic resources for use in future barley breeding programs. Despite the overall positive correlation of genotypes/cultivars, the best genotypes under aCO_2 might not always be the best genotypes under eCO_2; thus, direct selection under eCO_2 is needed to identify the best varieties for future climates.

4. Materials and Methods

4.1. Genetic Material and CO_2 Enrichment

Thirty Ethiopian barley cultivars consisting of 15 landraces and 15 released cultivars were obtained from Holetta Agricultural Research Centre (HARC) in Ethiopia. The landraces represent dominant barley landraces that are cultivated in different parts of Ethiopia. The released cultivars were chosen based on their diversity regarding adaptation and genetic background. They were released from 1975, are grown in different parts of the country, and differ in their traits such as grain yield (Figure A1, Table A1 and A2). The cultivars were cultivated in six identical climate chambers (Vötsch BioLine, Balingen, Germany) in which the climatic variables could be controlled. To mimic a realistic seasonal climate within the climate chambers, the daily temperature and relative humidity mean of Holeta from the period 2008–2018, and which are registered at World Weather Online (https://www.worldweatheronline.com, accessed on 12 January 2019), was used. In total, 27 weekly climate profiles were derived from these 10-year time series, representing the main growing season in Ethiopia. The day length (12 h) and the daily temperatures (daily mean of the coldest week: 8 °C; daily mean of the warmest week: 25 °C) were adapted. The CO_2 concentration within the chambers did not follow any time course but was set to constant values of 400 ppm in three chambers (ambient concentration, aCO_2) and 550 ppm in another three chambers (elevated concentration, eCO_2).

4.2. Plant Cultivation and Measurement of Plant-Related Parameters

The polyvinyl chloride pots used in the experiment were 40 cm in height and 10.3 cm in diameter, with a total volume of 3.33 L and a surface area of 83.33 cm^2. These pots were filled with 3.3 kg of sand and standard soil (Fruhstorfer Erde LD80, Hawita GmbH, Vechta, Germany) with a 2:1 ratio. The standard soil, LD80, comprised 50% peat, 35% volcanic clay, and 15% bark humus, and it was enriched with slow-releasing fertilizers. The pH ($CaCl_2$) of the medium was 5.9, the organic matter content was 35% (loss-on-ignition), and the salt content was 1 g L^{-1} KCl. The nutrient availability of the LD80 standard medium was (mg L^{-1}) 150 N, 150 P_2O_5, and 250 K_2O. Per cultivar, five seeds were grown and thinned at the seedling stage in two experimental plants per pot. Once a week, pots and CO_2 treatments were rotated between chambers to avoid any potential chamber effects. Plants were watered with 500 mL at the beginning of the experiment and were regularly watered throughout with an adequate amount to avoid drought. Pots were weighed once a week and adjusted to a weight of 5 kg to monitor differences in the water consumption of plants from different CO_2 treatments over time. The total water consumption ranged between 8.6 and 9.7 L in landraces and between 8.7 and 9.8 L in released cultivars. The values of total water use (WU_T, Equation (Eq. 1)), water-use efficiency of vegetative biomass (WUE_B, Equation (Eq. 2)), and water-use efficiency of grain yield (WUE_G, Equation (Eq. 3)) were calculated.

When the plants reached full maturity, plant height and total pot weight were measured before harvesting. Afterward, plants were harvested and separated into the vegetative biomass fractions (leaves, stems, and reproductive organs/ears). The single plant fractions were oven-dried at 30 °C (reproductive organs/ears) and 60 °C (stems and leaves) until they reached a constant weight before their dry weight was determined. The share to which single plant fractions contributed to total plant biomass was calculated and given as leaf, stem, and ear dry matter weight per plant. Grains were removed from the ears by manual threshing to determine the total grain yield, thousand-grain weight, and grain number, as well as the harvest index per plant.

$$WU_T = \frac{Total\ water\ applied\ (L)}{Plant} \quad (1)$$

$$WUE_B = \frac{Biomass\ yield\ (g)}{Total\ water\ applied\ (L)} \quad (2)$$

$$WUE_G = \frac{Grain\ yield\ (g)}{Total\ water\ applied\ (L)} \quad (3)$$

4.3. Statistical Analyses

The experiment was conducted using a randomized split-plot design with three replicates per CO_2 treatment level; the CO_2 treatment level was used as the main plot factor. The two levels of CO_2 were randomly assigned to a climate chamber, and cultivars were randomly placed in a climate chamber. Once a week, pots and CO_2 treatments were rotated between chambers to avoid any potential chamber effects. Following the experimental design, a two-way analysis of variance (ANOVA) was applied to test the significance of the main effects of genotype/cultivar and CO_2 treatments, as well as their interactions regarding both the landrace and released cultivars. In addition, the main effects of altitude and its interaction with CO_2 levels were analyzed regarding the landrace. Means were separated using Tukey HSD post hoc tests. Pearson's correlation coefficients were calculated to compare response variables and the performance of cultivars under the aCO_2 condition versus the eCO_2 condition. All the analyses were performed using the R programming language, version 4.0.1 [51].

5. Conclusions

Elevated CO_2 is beneficial to barley growth, yield, and water-use efficiency. The present study evaluated thirty Ethiopian barley cultivars and showed that eCO_2 levels provoke a significant enhancement of vegetative biomass and grain yield values. In comparison, grain yield was much more responsive to the eCO_2 condition than vegetative biomass, mainly due to a significant enhancement of the ear biomass value, grain number, and harvest index. The water-use efficiency of vegetative biomass and the water-use efficiency of grain was enhanced in future climate condition. The grain yield gain was positively associated with the high grain number and water-use efficiency of grain per plant. On average, the released cultivars benefited more from CO_2 fertilization than the landraces. However, a wide range of intraspecific variation was observed within the responses of biomass and grain yield parameters across both the landrace and released cultivars. For instance, the cultivars *Lan_15* and *Rel_4* were the highest yielding variants among the landrace and released cultivars, respectively, under the current and future CO_2 levels and represent important genetic resources for use in the future barley breeding in Ethiopia. The investigation of the interaction between cultivar types and the environment could help to better understand the thresholds for cultivars' performance under climate change conditions. Grain yield production under future climate conditions could benefit from the identification of cultivars with higher grain numbers and more efficient water use in grain. However, food security involves more than just production. Further attention is required regarding the investigation of the nutritional quality of barley cultivars under eCO_2 conditions. Moreover, the growth and stress tolerance values of Ethiopian barley cultivars in response to the interactive effects of eCO_2 conditions, warming, and drought should be examined in order to achieve better exploitation of germplasm resources under changing climatic conditions.

Author Contributions: M.W.G. conceived and designed the study; data collection was carried out by M.W.G.; M.W.G. and W.A.M. participated in the analysis of the data; M.W.G. wrote the paper, with substantial input from B.I.G.H. and W.A.M. All authors have read and agreed to the published version of the manuscript.

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Appendix A

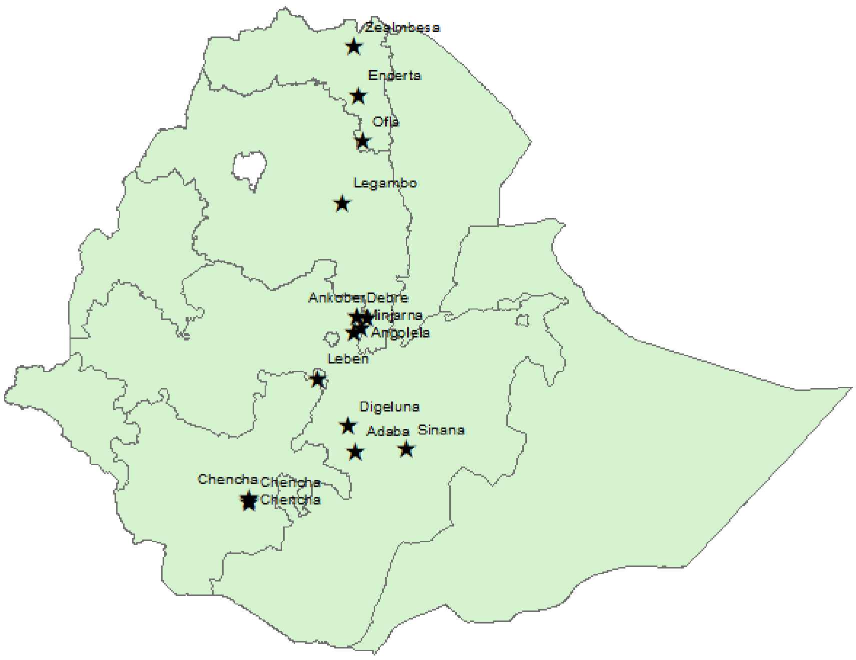

Figure A1. Map of origin of Ethiopian landrace cultivar collection.

Table A1. List of Ethiopian landrace cultivars and the origin of the collection.

Code	Cultivars	Region	Zone	Woreda	Latitude	Longitude	Altitude
Lan_1	215217-A	Amara	Debub	Legambo	11-39-00-N	39-00-00-E	3570
Lan_2	18330-A	Amara	Semen	Angolela	09-18-00-N	39-32-25-E	3325
Lan_3	219578-A	Amara	Semen	Debre	09-37-00-N	39-25-00-E	2690
Lan_4	243410	Amara	Semen	Ankober	09-36-00-N	39-44-00-E	2350
Lan_5	237021	Amara	Semen	Minjarna	09-10-20-N	39-20-00-E	1750
Lan_6	208816-A	Oromiya	Bale	Adaba	07-00-20-N	39-23-30-E	3500
Lan_7	237015	Oromiya	Arssi	Digeluna	07-45-00-N	39-11-00-E	2600
Lan_8	64233-C	Oromiya	Bale	Sinana	07-04-00-N	40-14-00-E	2460
Lan_9	18327	Oromiya	Semen	Leben	08-28-00-N	38-56-59-E	1642
Lan_10	216997	SNNP	Semen	Chencha	06-17-00-N	37-35-00-E	3030
Lan_11	208845	SNNP	Semen	Chencha	06-15-00-N	37-35-00-E	2850

Lan_12	234307	Tigray	Misrak Awi	Zealmbesa	14-16-00-N	39-21-00-E	3100
Lan_13	234293	Tigray	Debub Awi	Ofla	12-48-00-N	39-35-00-E	2410
Lan_14	237339	Tigray	Debub Awi	Enderta	13-30-00-N	39-28-00-E	2240
Lan_15	221325	SNNP	Semen	Chencha	06-09-00-N	37-36-00-E	2150

Table A2. List of Ethiopian released cultivars and their desired trait.

Code	Cultivars	Genetic Background/Pedigree	Year of Released	Desirable Traits of the Cultivars Other than Yield
Rel_1	Gobe	IICARDA germplasm-CBSS96Moo487T-D-1M-1Y-2M-oY	2012	
Rel_2	Cross 41/98	(50-16/3316-03)//(HB42/Alexis)	2012	High yielding, late maturing
Rel_3	EH 1493	White Sasa/Comp29//White Sasa/EH538/F2-12B-2	2012	High yielding, late maturing
Rel_4	EH1847	EH1847/F4.2P.5.2 (Beka/IBON64/91)	2011	
Rel_5	Bekji-1	EH 1293/F2-18B-11-1-14-18	2010	
Rel_6	HB-1307	EH-1700/F7. B1.63.70	2006	High yield, lodging resistant, resistant to leaf diseases (Pyrenophora teres and Rhynchosporium secalis), good biomass yield, and white seeded
Rel_7	Misccal-21	Azafran = Shyri//Gloria/Copal/3/Shyri/Grit; CMB87.643-2A	2006	High yield with good malting quality; resistance to lodging with multiple disease resistance
Rel_8	Meserach	Pure line selection- Kulumsa1/88	1998	Early maturing and tolerant to major leaf diseases (Pyrenophora teres and Rhynchosporium secalis)
Rel_9	HB-42	EIAR cross-IAR-H-81/comp29//comp14-20/coast	1984	Resistant to scalding (Rhynchosporium secalis) and good biomass yield
Rel_10	IAR/H/485	Pure line selection from local landrace in Arsi	1975	
Rel_11	Ardu 12-60B	Pure line selection from local landrace in Arsi	1986	
Rel_12	Balemi	Dominant farmers varieties in West shoa	1970	Tolerant to low soil fertility and drought, good flour quality
Rel_13	HB-1964	RECLA78//SHYRI/GRIT/3/ATAH92/GOB	2016	
Rel_14	HB-1965	Awra gebs X IBON64/91	2017	
Rel_15	HB-1966	CARDO/CHEVRON-BAR CBSS 96 WM 00019s	2017	

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5. Publication III

Simulating the effect of climate change on barley yield in Ethiopia with the DSSAT-CERES-Barley model

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Climate change and variability in Ethiopia, as well as their significant impact on barley production, are discussed in Chapter 5. The aim of this study was first to calibrate and evaluate the performance of the DSSAT-CERES-Barley model and second to investigate the possible impacts of climate change on Ethiopian barley production under projected climate scenarios using the DSSAT cropping system model (version 4.7.5). Furthermore, different sowing dates, sowing densities, and fertilizer levels were tested as climate change impact mitigation strategies in a sensitivity analysis. Climate change projections were made and compared to the baseline climate (1981-2010). Overall, the evaluated model represented the yield of barley cultivars grown at the experimental sites in Ethiopia satisfactorily. The results of five global circulation models run under two Representative Concentration Pathways (RCP 4.5 and 8.5) indicated that the future climate will be warmer than the baseline (1980-2010), with less rainfall. As a result, when all climate scenarios were averaged, yield gains of up to 15%, as well as a reduction of up to 98%, were observed under the future climate, depending on the location. The sensitivity analysis revealed that early sowing, increased sowing density, and increased N fertilizer rates will help to reduce the impact of climate change. However, analyzing combined adaptation strategies individually for each location and cultivar could help to develop better adaptation strategies. More research on plant-environment-management interactions is required in the future to increase agricultural productivity and improve food security.

Simulating the effect of climate change on barley yield in Ethiopia with the DSSAT-CERES-Barley model

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ARTICLE

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Simulating the effect of climate change on barley yield in Ethiopia with the DSSAT-CERES-Barley model

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Abstract

Climate change is expected to have a major effect on crop production in sub-Saharan Africa. Crop models can help to guide crop management under future climate. The objective of the study was to investigate the possible effects of climate change on Ethiopian barley (*Hordeum vulgare* L.) production using the Decision Support System for Agrotechnology Transfer (DSSAT)-Crop Environment Resource Synthesis (CERES)-Barley model. The study included field data of two barley cultivars (Traveller and EH-1493) and four climate study areas in Ethiopia over 5 yr. Climate change scenarios were set up over 60 yr using representative concentration pathways (RCP; RCP4.5 and RCP8.5) and five global climate models (GCM). The model results indicated that the prediction of days to anthesis and maturity, as well as final grain yield, was highly accurate for cultivar Traveller with normalized RMSE (nRMSE) of 2, 1, and 12%, respectively, and for cultivar EH-1493 with nRMSE of 2, 4, and 11%. A consistent increase in average temperature up to 5 ˚C and a mixed pattern of rainfall (-61 to +86%) were projected. Yield simulations showed a potential reduction in yield up to 98% for cultivar Traveller and 63% for cultivar EH-1493 in the future. Within a sensitivity analysis, different sowing dates, sowing densities, and fertilizer rates were tested as potential adaptation approaches to climate change. The negative effects of climate change could be mitigated by early sowing, with an increased sowing density of 25% and fertilizer rate of 50% more than what is recommended. Overall, the results indicated the ability of the CERES-Barley model to evaluate climate change effects and adaptation options on rainfed barley production in Ethiopia.

1 | INTRODUCTION

Climate change represents one of the major challenges of the 21st century and will have a major effect on agriculture. The latest and previous reports of the Intergovernmental Panel on Climate Change showed that the global average temperature has increased by 0.74 ˚C in the last century and is projected to increase within 1.1–5.8 ˚C by the end of this century. Further rainfall patterns will change with an increased frequency of extreme events (IPCC, 2018; Meehl et al., 2007). The effects of increased temperature and changes in rainfall patterns are expected to reduce agricultural production and put further pressure on the sector (Lobell & Field, 2007;

Abbreviations: CERES, Crop Environment Resource Synthesis; DSSAT, Decision Support System for Agrotechnology Transfer; GCM, global climate model; nRMSE, normalized RMSE; PHINT, Phylochon Interval; RCP, representative concentration pathway.

Van de Steeg et al., 2009). Numerous studies (Challinor et al., 2009; IPCC, 2014) conclude that the strongest effect of climate change on the economic output of agriculture is expected for sub-Saharan Africa, including Ethiopia. It is expected that the negative effects of climate change are more severe in developing countries and food-insecure regions, as rainfall is the predominant source of soil moisture to meet the plant-water demand for agricultural practices (Martinez et al., 2012; Tilahun, 2006).

In Ethiopia, agricultural production and its performance always follow seasonal climate patterns as seasonal rainfall is the key factor in local food production systems (NMA, 2007; Winthrop et al., 2018). Barley (*Hordeum vulgare* L.) is the fourth most important cereal crop in the world next to wheat, maize, and rice (Taner et al., 2004) and constitutes most of Ethiopia's crop agriculture and food economy (Mulatu & Glando, 2011; Taffesse et al., 2013). In Ethiopia, it is one of the major cereal crops grown following teff [*Eragrostis tef* (Zuccagni) Trotter], wheat (*Triticum aestivum* L.), maize (*Zea mays* L.), and sorghum [*Sorghum bicolor* (L). Moench]. Ethiopia is considered as a center of diversity for barley, having a long history of cultivation that is estimated to be 5,000 yr long (Gebre & Leur, 1996; Mulatu & Glando, 2011). Due to the diversity of Ethiopian environments, barley is grown from 1,800 to 3,400 m above sea level in various production systems (Bantayehu, 2013). This makes Ethiopia the second-largest barley producer in Africa, next to Morocco, accounting for about 25% of the total barley production in the continent (FAO, 2019). Despite its long history of production in Ethiopia, the current productivity of barley is decreasing due to the challenge of developing cultivars that can face production constraints such as poor genetic improvement, moisture stress/drought, and frost. Further limited agronomic practices are commonly indicated as major yield-limiting factors for barley (Gebre & Leur, 1996; Mulatu & Glando, 2011).

The Food and Agriculture Organization (FAO, 2012) strongly recommends the integration of climate information into agronomic management for risk management and adaptation planning to sustain the quality and quantity of agricultural production, especially in sub-Saharan Africa (WMO, 2004). Tools and approaches that evaluate production potential and needed agronomic adaptations to guide farmers are critically important to maximize and sustain agricultural development through managing production uncertainties (FAO, 2012). The Decision Support System for Agrotechnology Transfer (DSSAT) is widely used for the evaluation of agricultural production systems as a function of weather, soil, and management processes (Hoogenboom et al., 2019; Jones et al., 2003). The crop model DSSAT-Crop Environment Resource Synthesis (CERES)-Barley was used to evaluate the effect of future climate change scenarios on grain yield (Araya et al., 2021; Zinyengere et al., 2015). A study by Araya et al. (2021) also discussed the effect of climate change on barley production in Ethiopia. The study indicated that the negative effect of climate change in the future could be minimized by choosing different crop management practices such as timely sowing and N management. Within DSSAT-CERES-Barley, the daily crop growth rate is defined based on the amount of intercepted radiation by leaf area per area unit with the underlying mechanism of radiation use efficiency (Cammarano et al., 2020; Jamieson et al., 1995). In DSSAT-CERES-Barley, the phenological development of the plant is a function of temperature and photoperiod. Higher temperatures lead to a shorter duration of specific phenological phases, resulting in a shorter growing season and reduced yield (Cammarano et al., 2020). The amount of water in the soil during plant development is of critical importance for nitrogen uptake and plant water status. Because of the underlying mechanisms used in DSSAT-CERES-Barley regarding radiation, temperature, and water for simulating plant development, biomass, and final grain yield, the model was assumed to be a relevant tool for evaluating the effects of climate change and stresses under the given conditions in Ethiopia (Trnka et al., 2004; Hlavinka et al., 2010; Ko et al., 2018).

Thus, the overall objectives of the current study were (a) to calibrate and evaluate the performance of the DSSAT-CERES-Barley model and (b) to investigate the possible effects of climate change on Ethiopian barley production under projected climate scenarios using the DSSAT cropping system model (Version 4.7.5). Further, within a sensitivity analysis, different sowing dates, sowing densities, and fertilizer levels were tested as climate change effect mitigation strategies.

Core Ideas

- Effects of climate change on Ethiopian barley production were simulated using the CERES-Barley model.
- The model results indicated that the prediction of phenology and yield was highly accurate.
- A consistent increase in average temperature and a mixed pattern of rainfall were projected.
- The model estimate showed reduction of yield up to 98% for cultivar Traveller and 63% for cultivar EH-1493.
- Adaptation measures are needed to mitigate the negative effect of climate change on barley.

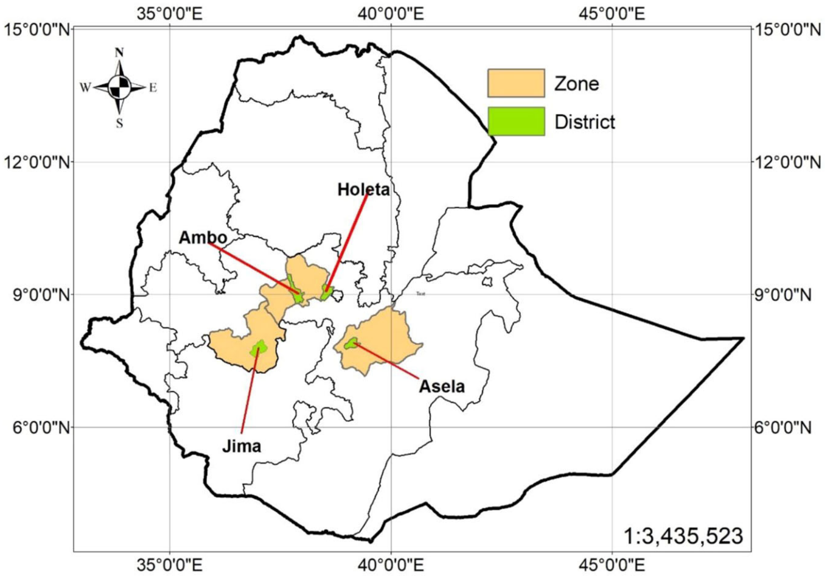

FIGURE 1 Map of the study areas Ambo, Asella, Holeta, and Jimma in Ethiopia

TABLE 1 Altitude, rainfall, minimum and maximum temperature of the selected study areas

Location	Altitude	Rainfall JJAS	Rainfall Annual	Tmax JJAS	Tmax Annual	Tmin JJAS	Tmin Annual
	m	mm		°C			
Asella	2,430	459.2	854.17	21.7	23.2	10.3	10.1
Ambo	2,101	760.3	1,106.3	25.3	26.3	10.3	10.5
Holeta	2,400	906.6	1,331.1	20.5	22.6	7.81	6.28
Jimma	1,780	884.3	1,628.5	24.9	26.4	13.3	12.2

Note. Tmax, maximum temperature; Tmin, minimum temperature; JJAS, main growing season from June to September.

2 | MATERIALS AND METHODS

2.1 | Study area description

Four locations in Ethiopia, namely Asella (7˚57′ N 39˚7′ E), Holeta (9˚3′ N 38˚30′ E), Ambo (8˚59′ N 37˚51′ E) and Jimma (7˚40′ N 36˚50′ E), were selected for the present study (Figure 1). The study areas are major barley- and wheat-growing belts found in the central and western highlands of Ethiopia. Asella is in the Arsi zone, which is categorized as a subtropical highland climate, while Ambo and Holeta are in central part of Ethiopia under the highland climate zone category (Figure 1). Jimma is in the western part of Ethiopia and is characterized by a cool tropical monsoon climate (Figure 1). The chosen locations highly differ in the amount of rainfall and temperature. The districts were selected based on their suitability for barley production and area coverage. Additional details about the locations are given in Table 1.

2.2 | DSSAT (CERES-Barley) model description

Decision Support System for Agrotechnology Transfer is a generic cropping-system model developed to simulate the growth, development, and yield of several crops grown on a homogenous area of land under a set of management conditions (Hoogenboom et al., 1992; 2019; Jones et al., 2003). The DSSAT-CERES-Barley is part of the DSSAT cropping-system model and simulates phenological events, reproductive development, dry matter accumulation throughout the growing season, and yield as a function of different soil, weather, and crop management conditions (Hoogenboom et al., 1992, 2019; Jones et al., 2003).

2.3 | Crop management data

Field experiment and crop management data for calibration and evaluation of the DSSAT-CERES-Barley were obtained

TABLE 2 Date of sowing and harvesting for cultivars EH-1493 and Traveller over the 5 yr experimental period (2015–2019) at Bekoji, Asella trial site

Cultivar	Sowing date	Harvest date
EH-1493	5 June 2015	10 Nov. 2015
EH-1493	28 June 2016	14 Nov. 2016
EH-1493	19 June 2017	19 Nov. 2017
EH-1493	29 June 2018	27 Nov. 2018
EH-1493	29 June 2019	4 Dec. 2019
Traveller	23 June 2015	5 Nov. 2015
Traveller	27 June 2016	28 Nov. 2016
Traveller	15 June 2017	9 Nov. 2017
Traveller	25 June 2018	25 Nov. 2018
Traveller	28 June 2019	1 Dec. 2019

TABLE 3 Average baseline (1980–2010) yield data (kg ha^{-1}) of cultivars Traveller and EH-1493 at the four study locations

Location	EH-1493	Traveller
	kg ha^{-1}	
Asella	4,466.3	3,682.9
Ambo	3,902.1	3,209.5
Holeta	4,161.4	3,444.2
Jimma	3,425.6	2,788.1

from the Kulumsa Agricultural Research barley and wheat research program. The experiment was part of the national variety trials conducted from 2015 to 2019 at the Bekoji, Asella trial site during the main cropping season (June to September) under rainfed conditions. Growth and phenology data including management practices for two barley cultivars, Traveller (malt barley) and EH-1493 (food barley) were used for model calibration and evaluation. These barley cultivars were released by Holeta Agricultural Research Centre of Ethiopian Institutes of Agricultural Research for midland and highland barley target growing areas. Sowing was done by hand with a density of 165 plants m^{-2} using a row spacing of 20 cm and a sowing depth of 5 cm. Recommended fertilizer rate for barley production in Ethiopia is 100 kg ha^{-1} of diammonium phosphate and 100 kg ha^{-1} of urea. One hundred kilograms per hectare of diammonium phosphate and 50 kg ha^{-1} urea were applied at sowing and an additional 50 kg ha^{-1} of urea was broadcast 35 to 40 d after sowing. The sowing and harvest date for each cultivar over the five experimental years are listed in Table 2. The historical yields of cultivars Traveller and EH-1493 were simulated for the baseline period (1981–2010) to calculate the yield deviations under predicted future climate change. Simulation of yield for the historical and the future climate scenario was done under rainfed conditions because no irrigation practice for barley production in Ethiopia exists. The average baseline yields for each cultivar and location are listed in Table 3.

2.4 | Weather and soil data

For each study area, daily weather, rainfall, and temperature data were obtained from the National Meteorological Agency of Ethiopia and Ethiopian Institutes of Agricultural Research database archives for the field experiment (2015–2019) as well as for the baseline period (1981–2010). Solar radiation data required for running the DSSAT model were incomplete from observation and thus were estimated using the WeatherMan climate data management tool shared with DSSATv4.7.5. WeatherMan uses sunshine hours, longitude, and latitude data of the specific study areas for the calculation of solar radiation.

Location-specific climate change scenarios were modeled using the delta method downscaling approach where monthly changes in temperature and precipitation were calculated from coupled atmosphere-ocean general circulation models. The delta method downscaling approach assumes that model biases for both mean and variability of future climate will be the same as the present-day simulations (Mote and Salathe, 2010). In this regard, scenario data for five global climate models (GCMs) (Table 4) were developed for mid- (2040–2069) and end-century (2070–2099) projections under the representative concentration pathways' (RCP4.5 and RCP8.5) emission scenario assumptions using the fifth coupled model inter-comparison project. Representative concentration pathways are methods or assumptions used to capture future climate scenario development processes by integrating economic, social, and physical factors that affect climate change. The RCP4.5 and RCP8.5 assume that CO_2 is elevated, with concentrations of 499 and 571 ppm, respectively, while solar energy striking the earth is assumed to be 4.5 and 8.5 wm^{-2}, respectively, by the end of the 21st century (Rosenzweig et al., 2016).

Soil profile data for the specific sites Asella, Ambo, Holeta, and Jimma were obtained from Africa Soil Information Service digital database v.1.2. The Africa Soil Profiles Database v.1.2 is derived from 54 data sources, where 25% of the data was extracted from International Soil Reference and Information Centre datasets, 30% from other digital datasets, and 45% from analog reports (Leenaars et al., 2014). Soil physical and chemical property data for the study locations were obtained from Africa Soil Information Service digital soil profile database archive (Table 5).

TABLE 4 Coupled model intercomparison project phase 5 (CMIP5) global climate models (GCMs) used for this study

GCM	Institute	Country	Latitude	Longitude	Resolution
			——(°)——		
ACCESS1.0	Commonwealth Scientific and Industrial Research Organization/Bureau of Meteorology	Australia	1.87	1.25	Medium
HadGEM2-ES	Met Office Hadley Centre	UK-Exeter	1.75	1.25	Medium
MPI-ESM-MR	Max Planck Institute for Meteorology	Germany	1.87	1.87	Medium
MRI-GCM3-	Meteorological Research Institute	Japan	1.12	1.12	High
INM-CM4	Institute for Numerical Mathematics	Russia	2	1.5	Medium

TABLE 5 Soil physical and chemical characteristics for the study areas Asella, Jimma, Holeta, and Ambo

Location	SLB	SLLL	SDUL	SSAT	SRGF	SSKS	SBDM	SLOC	SLCL	SLSI	SLHW	SCEC
	cm	$cm^3\ cm^{-3}$	$cm^3\ cm^{-3}$	$cm^3\ cm^{-3}$		$cm\ h^{-1}$	$g\ cm^{-3}$	——%——			pH	$cmol\ kg^{-1}$
Asella	10	0.23	0.36	0.44	1.00	0.18	1.13	1.40	38.5	28.8	6.6	51.7
	30	0.24	0.37	0.45	0.85	0.15	1.15	0.87	40.4	27.9	6.6	45.3
	60	0.26	0.39	0.46	0.70	0.12	1.18	0.69	43.1	26.9	6.7	43.9
	90	0.27	0.40	0.47	0.50	0.09	1.23	0.63	45.4	25.8	6.8	45.9
	120	0.27	0.40	0.47	0.38	0.09	1.29	0.61	45.4	25.1	7.0	46.2
	150	0.26	0.39	0.46	0.05	0.10	1.34	0.60	44.0	24.7	7.2	46.1
	180	0.26	0.39	0.46	0.05	0.10	1.34	0.60	44.0	24.7	7.2	46.1
Jimma	10	0.23	0.36	0.45	1.00	0.14	1.14	1.40	38.9	30.4	6.0	36.8
	30	0.24	0.38	0.45	0.85	0.12	1.16	0.87	41.0	29.6	6.1	32.3
	60	0.26	0.39	0.46	0.70	0.10	1.19	0.69	43.3	28.6	6.2	31.3
	90	0.27	0.40	0.47	0.50	0.08	1.24	0.63	45.7	27.4	6.3	32.7
	120	0.27	0.40	0.47	0.38	0.08	1.30	0.61	45.8	26.7	6.4	32.9
	150	0.26	0.39	0.46	0.05	0.08	1.35	0.60	44.5	26.4	6.6	32.8
	180	0.26	0.39	0.46	0.05	0.08	1.35	0.60	44.5	26.4	6.6	32.8
Holeta	10	0.23	0.36	0.44	1.00	0.14	1.08	1.40	39.0	22.5	6.2	34.6
	30	0.24	0.37	0.44	0.85	0.11	1.10	0.87	40.9	21.8	6.3	30.3
	60	0.26	0.38	0.45	0.70	0.08	1.13	0.69	43.5	20.7	6.4	29.4
	90	0.27	0.40	0.46	0.50	0.06	1.18	0.63	45.6	19.7	6.5	30.7
	120	0.27	0.40	0.46	0.38	0.06	1.24	0.61	45.7	19.1	6.6	30.9
	150	0.26	0.39	0.45	0.05	0.07	1.30	0.60	44.1	18.8	6.8	30.8
	180	0.26	0.39	0.45	0.05	0.07	1.30	0.60	44.1	18.8	6.8	30.8
Ambo	10	0.24	0.37	0.45	1.00	0.13	1.19	1.40	40.5	28.4	6.6	44.7
	30	0.25	0.38	0.46	0.82	0.11	1.21	0.87	42.3	27.6	6.7	39.1
	60	0.27	0.40	0.47	0.65	0.09	1.24	0.69	44.9	26.5	6.8	38.0
	90	0.28	0.41	0.47	0.38	0.07	1.29	0.63	47.2	25.4	6.9	39.8
	120	0.28	0.41	0.47	0.19	0.07	1.35	0.61	47.2	24.8	7.0	40.0
	150	0.27	0.40	0.47	0.05	0.08	1.41	0.60	45.8	24.4	7.2	39.9

Note. SBDM, soil bulk density; SCEC, soil cation exchange capacity; SDUL, soil layer upper limit; SLB, soil depth of bottom layer; SLCL, soil clay content; SLHW, pH in water; SLLL, soil layer lower limit; SLOC, soil organic carbon; SLSI, soil silt content; SRGF, soil root growth factor; SSAT, soil layer saturation; SSKS, soil saturated hydraulic conductivity.
Source: Africa Soil Information Service digital soil map.

TABLE 6 Calibrated parameters of the DSSAT-CERES-Barley for Traveller and EH-1493

Genetic coefficient	Description	Traveller	EH-1493
P1V	Days, optimum vernalizing temperature, required for vernalization	35.7	19.5
P1D	Photoperiod response (% reduction in rate 10 h^{-1} drop in pp)	20.12	23.55
P5	Grain filling (excluding lag) phase duration (°C d^{-1})	538.3	515.2
G1	Kernel number per unit canopy weight at anthesis (number g^{-1})	15.22	17.43
G2	Standard kernel size under optimum conditions (mg)	47.36	50.04
G3	Standard, nonstressed mature tiller weight (incl grain) (g dry weight)	1.004	0.682
PHINT	The interval between successive leaf tip appearances (°C d^{-1})	89	89

2.5 | Model calibration and evaluation

To better capture the growth and development response of crops for the representative environments, cultivar coefficient adjustment (calibration) and model evaluation are major pre-condition activities to be undertaken before trying to use the model for further application (Guereña et al., 2001; Hoogenboom et al., 1992). The DSSAT-CERES-Barley model was calibrated using observed field experiment data, conducted in 2015 and 2016 during the main cropping season at the Bekoji, Asella field research trial site. To optimize the seven DSSAT-CERES-Barley cultivar specific parameters (genetic coefficients, Table 6) as described in Jones et al. (2003), crop growth and phenology data were collected following the procedures indicated in Hoogenboom et al. (1992) and Hunt et al. (1993). The Generalized Likelihood Uncertainty Estimation tool was used to estimate cultivar-specific coefficients for the two barley cultivars, except for the parameter Phylochron Interval (PHINT). The toolwas not able to successfully estimate PHINT and resulted in high uncertainty. GenCalc was used to optimize PHINT as it was able to adjust this coefficient with higher accuracy of the model (Ibrahim et al., 2016). The coefficients are expressed in terms of thermal time and photoperiod requirements for phenology and growth/reproductive parameters (Table 6).

Once the model parameters were adjusted using measured field data, the calibrated model was further evaluated using three years (2017–2019) of field data collected from the Bekoji, Assela crop field research site. Evaluation of model performance was done using the coefficient of determination (R^2, Equation 1), RMSE (Equation 2), and normalized RMSE (nRMSE) (Equation 3). R^2 values that are 1 or close to 1 and RMSE values close to 0 indicate perfect fits between simulated and observed data, and nRMSE values <10% indicate an excellent model performance as well (Jamieson et al., 1995).

$$R^2 = 1 - \frac{\text{RSS}}{\text{TSS}} \tag{1}$$

where RSS is the sum of squares of residuals, and TSS is the total sum of squares.

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (P_i - O_i)^2}{n}} \tag{2}$$

where n is the number of observations, P_i is the calculated value for the ith measurement, and O_i is the observed value for the ith measurement.

$$n\text{RMSE} = \frac{\text{RMSE} \times 100}{\bar{o}} \tag{3}$$

where RMSE is the root mean square error, and $\bar{o}$ is the mean of the observed values.

2.6 | Sensitivity analysis

Within a sensitivity analysis, different sowing dates, sowing densities, and fertilizer levels were tested as potential adaptation strategies to climate change. The simulation was carried out to test the potential yield estimate changes of both cultivars (Traveller and EH-1493) at four locations. The range of sowing dates was simulated between June and July, at 15-d intervals covering the typical range of barley sowing windows in Ethiopia (early: 1–15 June, normal: 16–30 June, and late: 1–15 July). Three sowing densities (normal: 165 plants m^{-2}, high: 25% higher than the normal, and low: 25% less than the normal) were simulated. In addition, three fertilizer rates (normal: 100 kg ha^{-1} of diammonium phosphate and 100 kg ha^{-1} of urea, high: 50% higher than the normal, and low: 50% lower than the normal) were simulated. The simulations were run for each sowing date over the baseline climate data and for all GCMs under mid- and end-century scenarios. Percentage of yield changes for each adaptation strategy, study area, and cultivar was calculated.

TABLE 7 Model calibration performance for days to anthesis, days to maturity, and grain yield at maturity for Traveller and EH-1493 averaged across two years (2015–2016)

Variables	EH-1493 Sim.	Obs.	R^2	RMSE	nRMSE	Traveller Sim.	Obs.	R^2	RMSE	nRMSE
					%					%
Days to anthesis	84	90	.9	6	7	86	86	.9	4	5
Days to maturity	139	136	.9	4	3	142	142	.9	2	1
Grain yield, kg ha^{-1}	4,125	3,714	.9	454	12	3,460	3,594	.9	136	4

Note. Sim., simulated; Obs., observed; nRMSE, normalized RMSE.

3 | RESULTS

3.1 | Model calibration

The genetic coefficients, as obtained by the Generalized Likelihood Uncertainty Estimation tool, are shown in Table 6. There was a considerable variation among the two barley cultivars in all parameters except for PHINT. Phylochron Interval was optimized using GenCalc for better model accuracy, and similar results were obtained for both cultivars (Table 6). The statistical indices for calibration of simulated and observed values showed high accuracy for crop phenology and yield (Table 7). The estimated RMSE values for cultivar EH-1493 indicated a difference of six days for days to anthesis and four days for days to physiological maturity with an nRMSE of 7 and 3%, respectively (Table 7), when averaged over two years (2015 and 2016). The model performance for yield was acceptable for cultivar EH-1493, represented by a nRMSE value of 12% (Table 7). Similarly, acceptable model performance was obtained for cultivar Traveller as shown in Table 7. Residual mean standard error values for cultivar Traveller showed a four-day difference to flowering with a nRMSE of 5% and a two-day difference for days to maturity with a nRMSE of 1%. The accuracy of the model in predicting grain yield for cultivar Traveller was very good with a nRMSE value of 4% (Table 7).

3.2 | Model evaluation

The performance of the DSSAT-CERES-Barley model was evaluated using three years of data (2017–2019), which were not used in the cultivar coefficient estimation process. All simulated and observed variables (anthesis, maturity, and grain yield) were compared and presented graphically in Table 8, Figure 2, and Figure 3 for the cultivars Traveller and EH-1493, respectively. Model evaluation with the calibrated cultivar parameters provided, in general, a good agreement between simulated and observed values of crop phenology and grain yield for both cultivars as can be seen in Table 8 (averaged across three years).

3.3 | Climate change projection

Future climate forecasts were downscaled at a local level using methods developed by the Agricultural Model Intercomparison and Improvement Project (Rosenzweig et al., 2016). The relative changes of future temperatures compared with the baseline period (1981–2010) for RCP4.5 and 8.5 are shown in Table 9. The results indicated that the average annual and seasonal temperatures will increase for both mid- (2040–2070) and end-seasons (2070–2100) as simulated by the five GCMs for the two RCPs (Table 9). The average temperature is projected to increase for all scenarios and periods for all study area locations. The projected increase in average temperature during the crop growing season was estimated to reach up to 5.1 ˚C for RCP8.5 (Table 9).

On the other hand, projections based on ten combinations (i.e., five GCMs with two RCP scenarios for precipitation) indicated mixed results, including decreases and increases in rainfall for the four locations under all periods and RCPs (Figure 4). The highest increases in total precipitation were projected under RCP4.5 for the end-season by GCM MPI-ESM-MR. Consistent increases in projected precipitation were observed by GCM MPI-ESM-MR under all periods and RCPs, while consistent decreases were observed by GCMs MRI-CGCM3 and ACCESS1-0 (Figure 4). Comparing the locations, a high variability on the projection of precipitation was observed for Asella and ranged from −61.4 to +86.1% by different models under both RCPs (Figure 4).

3.4 | Grain yield response under future climate scenarios

The simulated barley grain yield for rainfed production systems showed a considerable decrease for all climate change scenarios and locations, except for a yield increase observed for cultivar EH-1493 in Holeta (Figures 5 and 6). A similar trend of reduction in grain yields up to 98% was observed for cultivar Traveller under both RCPs and for all locations (Figure 5). The simulation for EH-1493 at Holeta showed a mixed trend between an enhancement of yield by 14.7% to a

TABLE 8 Model evaluation for days to anthesis, days to maturity, and grain yield at maturity for Traveller and EH-1493 averaged across 3 yr (2017–2019)

	EH-1493					Traveller				
Variables	Sim.	Obs.	R^2	RMSE	nRMSE	Sim.	Obs.	R^2	RMSE	nRMSE
					%					%
Days to anthesis	94	93	.8	2	2	96	98	.8	2	2
Days to maturity	154	155	.6	2	1	159	153	.9	6	4
Grain yield, kg ha^{-1}	5,032	5,498	.8	635	12	4,356	4,522	.8	509	11

Note. Sim., simulated; Obs., observed; nRMSE, normalized RMSE.

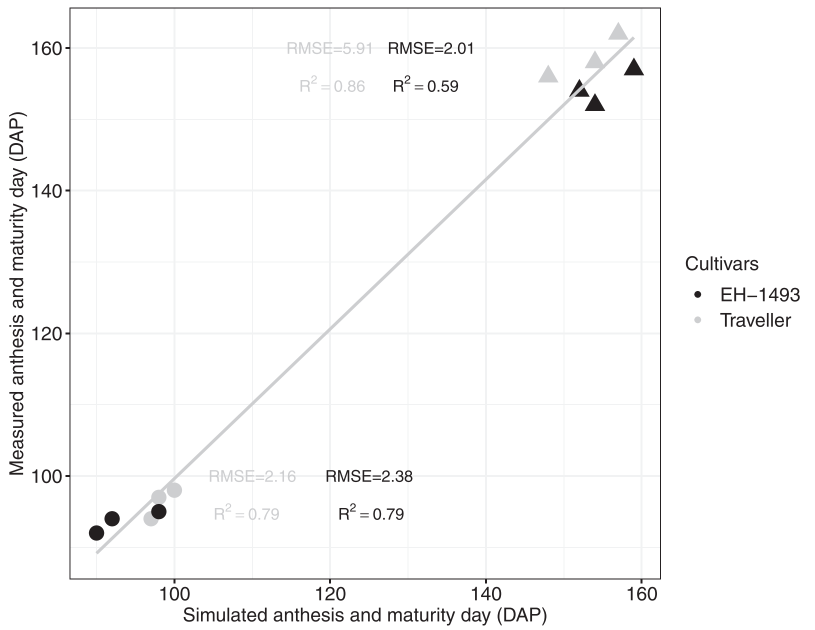

FIGURE 2 Comparison of simulated and observed anthesis (circles) and maturity (triangles) as days after sowing (DAP) for Traveller and EH-1493 averaged across 3 yr (2017–2019)

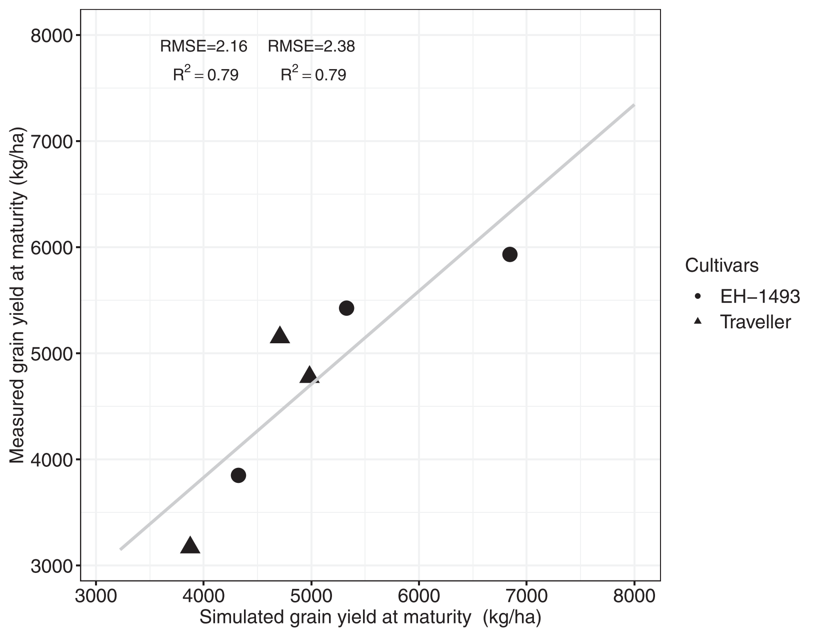

FIGURE 3 Comparison of simulated and observed grain yield (kg ha^{-1}) for Traveller and EH-1493 averaged across 3 yr (2017–2019)

TABLE 9 Projected change in temperature for the mid- (2040–2069) and end-season (2070–2100) compared with the baseline (1981–2010)

	Tmax				Tmin			
	RCP 4.5		RCP 8.5		RCP 4.5		RCP 8.5	
Station	JJAS	Annual	JJAS	Annual	JJAS	Annual	JJAS	Annual
	°C							
Mid-century (2040–2069)								
Ambo	1.5	1.5	2.3	2.3	1.7	1.9	2.7	3.0
Jimma	1.7	1.6	2.5	2.4	1.7	1.9	2.6	2.9
Holeta	1.9	1.8	2.4	2.3	1.8	1.9	2.6	2.8
Asella	2.0	1.8	2.6	2.3	1.8	2.0	2.5	2.7
End-century (2070–2099)								
Ambo	2.0	1.9	4.0	3.9	2.4	2.6	4.6	5.1
Jimma	1.7	1.6	4.2	4.1	2.2	2.4	4.4	4.9
Holeta	2.5	2.3	4.3	3.9	2.3	2.6	4.4	4.9
Asella	2.6	2.2	4.4	3.8	2.3	2.6	4.3	4.7

Note. Tmax, maximum temperature; Tmin, minimum temperature; JJAS, main growing season from June to September.

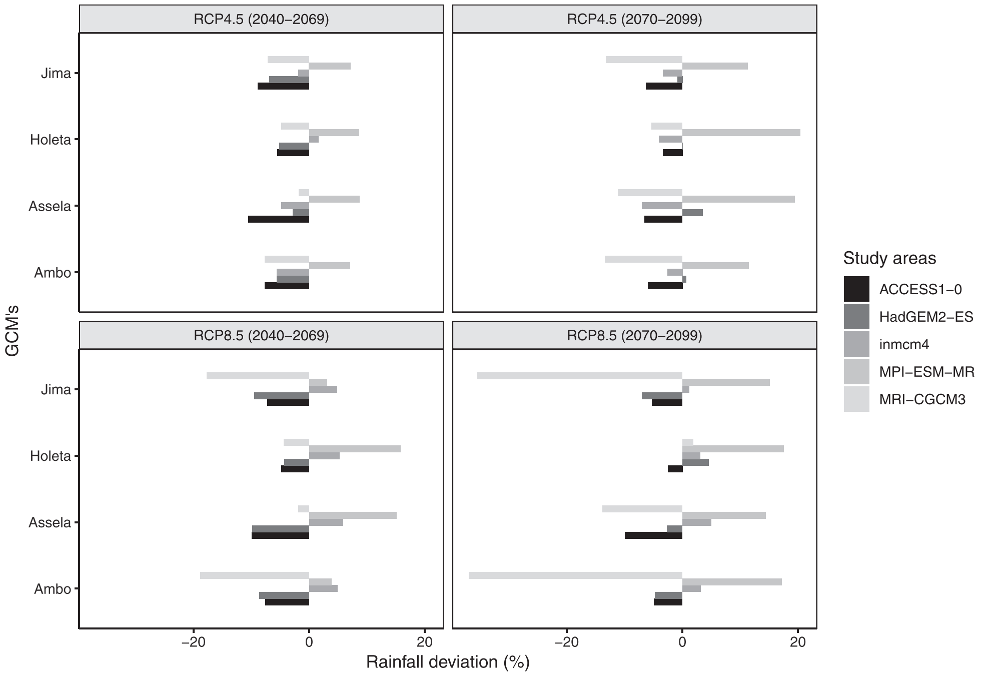

FIGURE 4 Projected changes in average precipitation of mid-season (2040–2069) and end-season (2070–2099) under RCP4.5 and RCP8.5 scenarios for five global climate models (GCMs) relative to the baseline period

reduction of up to 63% under the tested future climate scenarios. However, the results were inconsistent between the different models (Figure 6). Overall, the negative effect of climate change on barley production at Holeta was lower compared with the other study locations, while the highest reduction in grain yield was projected for Jimma (98%) under the RCP8.5 end-term by the MPI-ESM-MR model compared with the baseline period (Figure 5).

3.5 | Sensitivity analysis: Effect of different sowing dates, fertilizer levels, and sowing density on barley yield

Sensitivity analysis on sowing date variation was analyzed for all four locations under two RCPs and five models. A similar trend was observed between the two cultivars on the response of sowing date variations under all conditions (Figure 7).

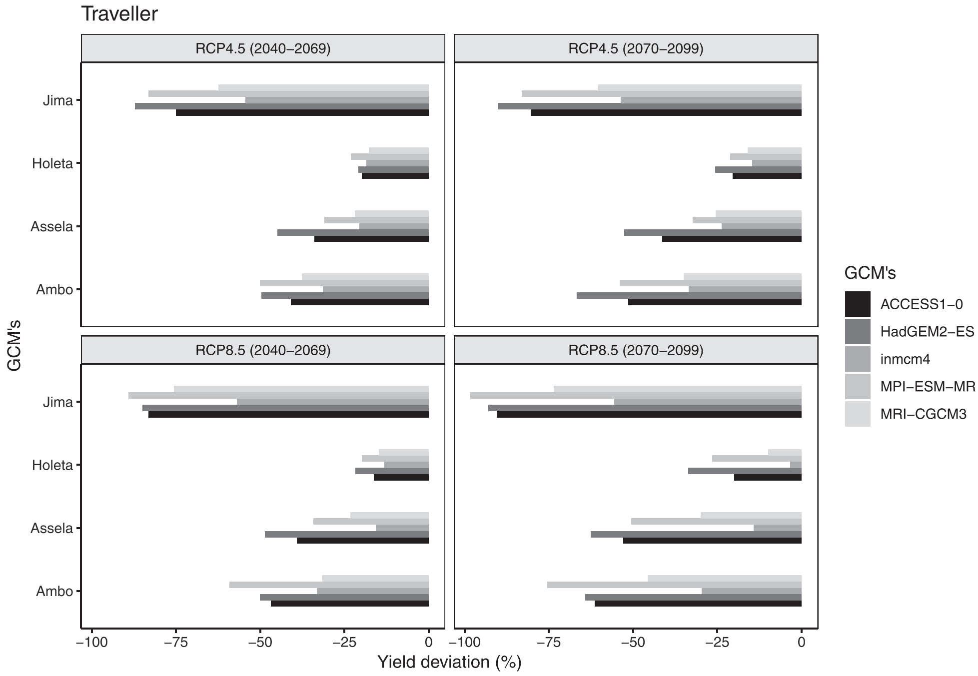

FIGURE 5 Simulated changes in barley grain yield for the tested future climate scenarios at four locations for cultivar Traveller

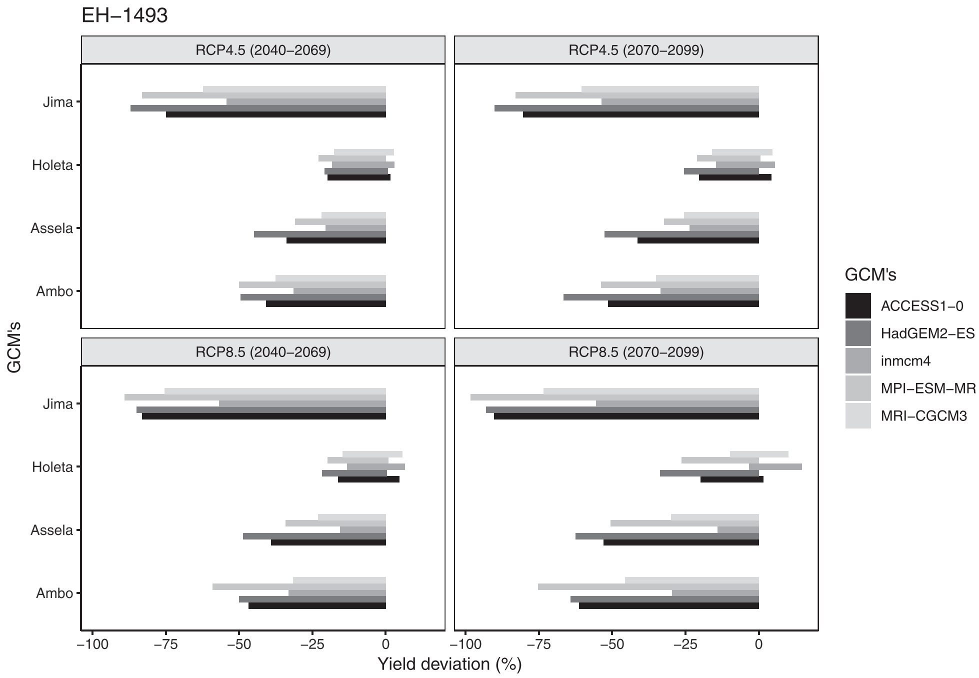

FIGURE 6 Simulated changes in barley grain yield for the tested future climate scenarios at four locations for the cultivar EH-1493

However, for Holeta all three adaptation strategies simulated in the present study indicated better mitigation of the potential negative climate change effects on barley production compared with the other sites. Comparing barley yield production across the locations, an increase of yield up to 16% was observed for Holeta compared with the baseline at the early- (1–15 June) and normal- sowing windows (16–30 June) as shown in Figure 7, while the negative effect was lower at

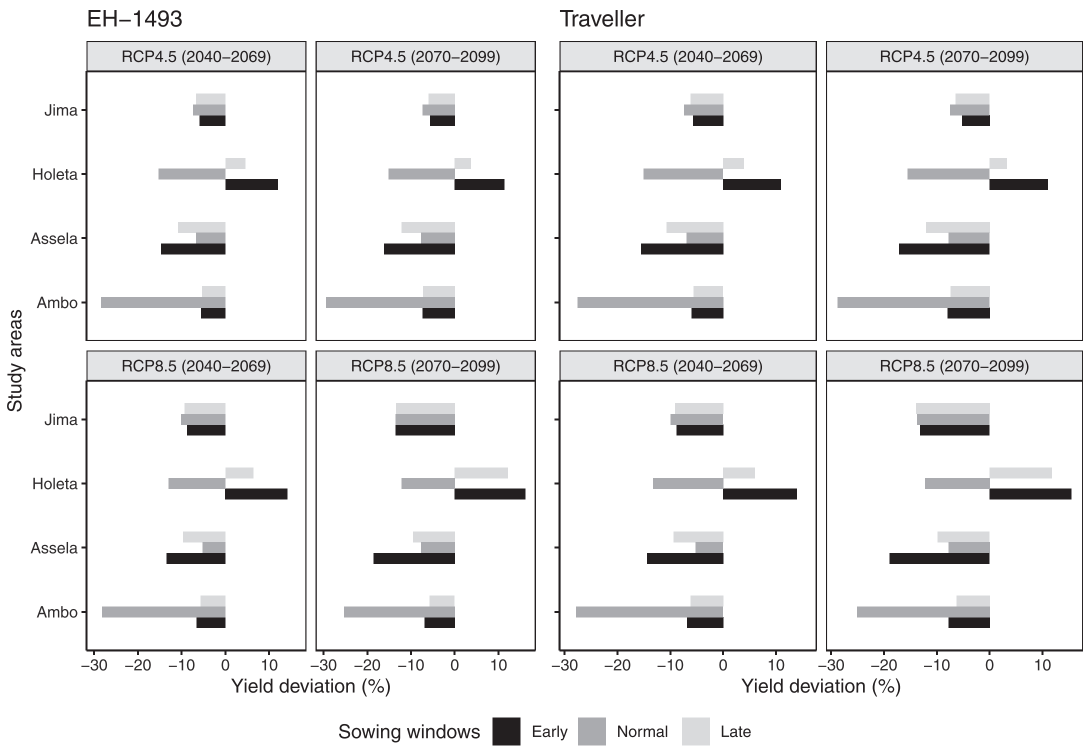

FIGURE 7 The percentage change of barley yield of two cultivars (EH-1493 and Traveller) from the baseline yield (1981–2010) under different sowing windows (early: 1–15 June; normal: 16–30 June; late: 1–15 July)

Ambo and Jimma. Nevertheless, a higher reduction of yield was projected under both RCPs for the late sowing window (1–15 July) except for Assela as shown in Figure 7.

Three sowing density rates were simulated over the study locations and two cultivars under all climate change scenarios for both cultivars EH-1493 and Traveller. Increasing sowing density by 25% more than the recommended 165 plants m^{-2} was beneficial at all locations under the future climate, according to model estimates. A positive response of yield up to 16% was recorded at Holeta under a higher sowing density, while the negative effect of climate change was almost zero at the other locations (Figure 8). The highest reduction of yield up to 30% due to climate change was observed with a 25% lower sowing density at all locations and scenarios (Figure 8). A less negative effect of climate change on yield was observed for cultivar EH-1493 when sowing density was increased by 25% more than the normal. However, cultivar Traveller showed a better response under 25% lower sowing density.

Increasing fertilizer rate by 50% in comparison with the currently recommended rate (100 kg diammonium phosphate ha^{-1} and 100 kg urea ha^{-1}) showed a positive response of yield, according to the crop model estimates. A yield increase of up to 22% was observed at Holeta compared with the baseline (1980–2010) under the higher fertilizer level. At the other locations, the estimated yield reduction was lower under higher fertilizer levels compared with normal and low fertilizer levels. Relatively higher reduction of yield up to 43% under future climate change was observed with a 50% lower fertilizer rate than the recommended (Figure 9). Both cultivars (cultivars EH-1493 and Traveller) showed less effect of climate change when the fertilizer level increased by 50% more than normal. On the other hand, the effect was high when the fertilizer level decreased by 50% on both cultivars than the lower and normal levels of fertilizer.

4 | DISCUSSION

4.1 | DSSAT-CERES-Barley model performance

Researchers around the globe have used DSSAT models for simulating climate change's effect on potential future yield (Araya et al., 2012; Endalew, 2019; Iglesias, 2009; Jiang et al., 2021; Paff & Asseng, 2019). Performance of the DSSAT model for simulating barley phenology, yield, soil water, and climate change effects are documented in many studies (Cammarano et al., 2020; Brogan, 2019; Hlavinka et al., 2010;

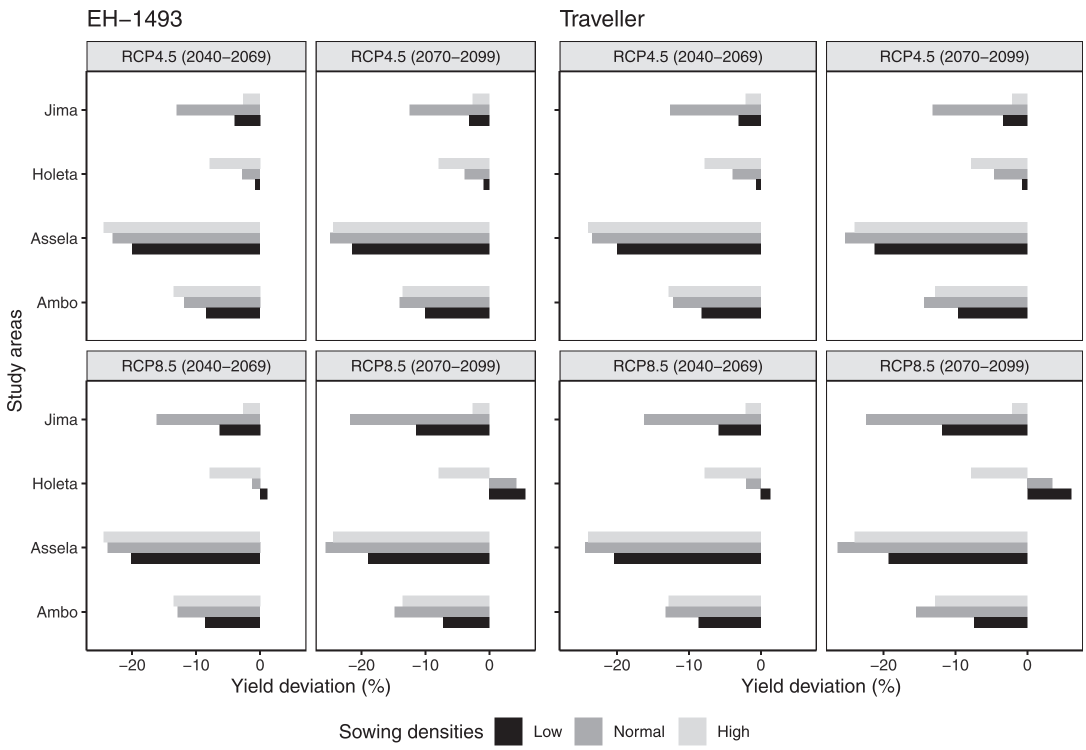

FIGURE 8 The percentage change of barley yield of two cultivars (EH-1493 and Traveller) from the baseline yield (1981–2010) under different sowing densities (high: 25% higher than the normal; normal: 165 plants m^2; 25% less than normal)

Rötter et al., 2012). In addition, a study that compared nine different crop models on simulating barley yield revealed that observed mean yields and variability were best captured by DSSAT-CERES (based on radiation use efficiency mechanism) compared with the others (Rötter et al., 2012). In the current study, the genetic coefficients for barley were adjusted to cultivars grown in Ethiopia under the given environmental conditions. The calibration results showed a good agreement between the simulated and observed data. The percent of deviation between simulated and observed days to anthesis and maturity was less than 5%, which is in line with Araya et al. (2021). The model simulated the observed days to anthesis and maturity with RMSEs of 2 and 6 d, respectively, for Traveller and 2 d for EH-1493 each. Likewise, a good simulation performance of the model for anthesis and maturity was observed in previous studies on barley (Cammarano et al., 2020; Brogan, 2019; Rötter et al., 2012). In this study, the model simulated the grain yield with a RMSE of 634.6 and 508.9 kg ha^{-1} for EH-1493 and Traveller, respectively (Figure 2). These values are lower than the values obtained by Cammarano et al. (2020) with a RMSE of 1,200 kg ha^{-1} but higher than the values with a nRMSE of 9% reported by Malik and Dechmi (2019). In addition, there was a strong linear relationship between simulated and measured grain yield ($R^2 > .8$) for both cultivars in the present study. Hlavinka et al. (2010) evaluated the performance of the DSSAT model for simulating barley yield with a relative mean bias error of -19.6 to 37.0% and nRMSE of 6.3 to 37.5%. Similarly, a strong agreement was reported between the simulated and measured barley yield with a nRMSE of 10 to 13.3% and R^2 of .89 to .9 (Brogan, 2019). Overall, the model calibration and evaluation acceptably represented the barley cultivars grown at the experimental site. The model simulation performance has been consistently good based on the past and present studies, indicating that the DSSAT-CERES-Barley model can be used for simulating barley yield and phenology under different climate conditions.

4.2 | Climate change and its implication on barley production

Regional climate projections and a clear understanding of their effect on crop production are needed for relevant adaptations of agronomic practices (Alemayehu & Bewket, 2016). The projections under RCP4.5 and RCP8.5 for the mid- and end-century showed considerable changes in temperature and precipitation in different locations in Ethiopia. Relative to the baseline (1980–2010), the mean temperature at the tested growing sites will increase by 1.5–5.1 ˚C according to the

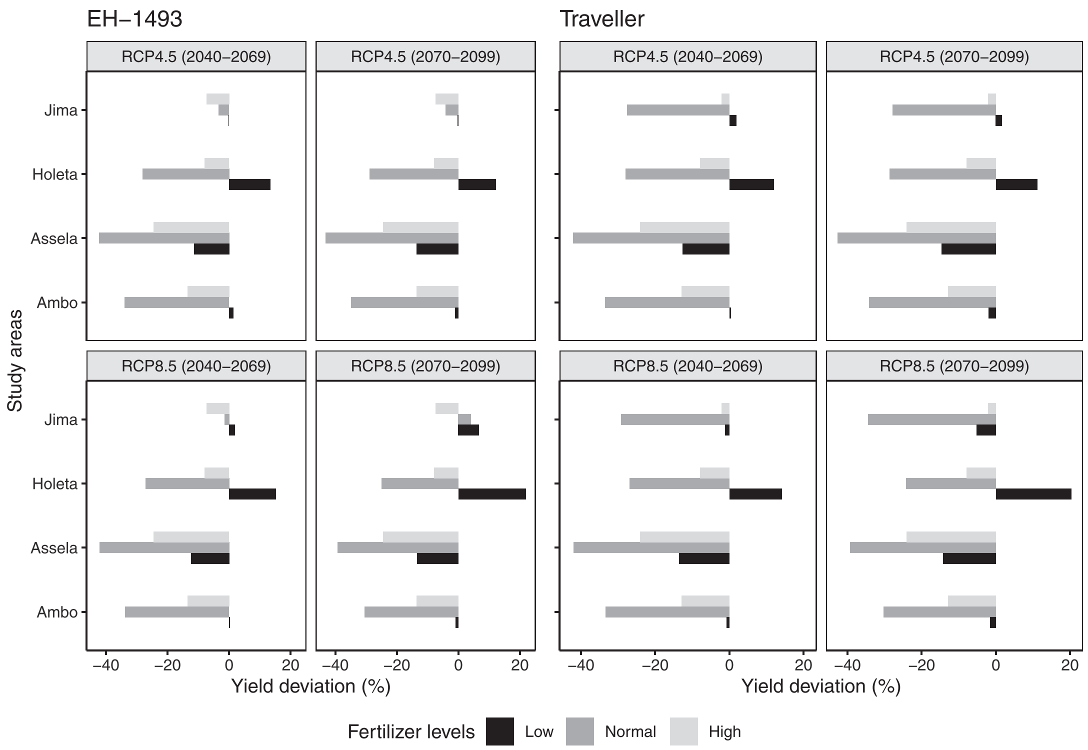

FIGURE 9 The percent change of barley yield of two cultivars (EH-1493 and Traveller) from the baseline yield (1981–2010) under different fertilizer levels (high: 50% higher than normal; normal: 100 kg diammonium phosphate ha^{-1} and 100 kg urea ha^{-1}; low: 50% lower than normal)

present study. The results indicated that the future climate will be warmer than the baseline period, which is in line with previous studies (Araya et al., 2019; Kassie et al., 2014). Even though the presented temperature changes varied over the study areas and across the five GCMs, projections showed a clear and consistent increase of the minimum and maximum temperatures at all locations. This is in agreement with previous reports that predicted higher air temperatures in the different regions of Ethiopia (Ayalew et al., 2012; Conway & Schipper, 2011; Carins et al., 2013).

The projections for precipitation showed mixed variation patterns between −61.4 to +86.1% across the four locations and the five GCMs. In line with the current finding, previous studies from Ethiopia indicated an increase in temperature with mixed projections were reported for precipitation (Conway & Schipper, 2011; Muluneh et al., 2017; NMA, 2007; Woldeamlak & Conway, 2007). However, some studies have identified a clear increasing trend of precipitation, up to 38%, in different parts of Ethiopia (Kassie et al., 2014; Muluneh et al., 2017). In addition, different projections have shown that East African highlands, including Ethiopia, will experience higher rainfall in the coming 50 yr accompanied by a high degree of temporal and spatial variability (IPCC, 2014; Omondi et al., 2014; Spinoni et al., 2014).

In the present study, simulations indicated a yield reduction for cultivar Traveller from 3 to 98%. The results were consistent over all study areas and climate scenarios. However, the projection for cultivar EH-1493 showed mixed results between 15% yield increase to 98% reductions. Yield increases up to 15% for cultivar EH-1493 were observed at Holeta under both RCPs. The reason for this yield increase can be attributed to the baseline temperature at Holeta, which was lower by about 2 ˚C when compared with the other study areas. So, the projected increased temperature up to 4.9 ˚C might not affect the production in the area to the same extent. Temperature is one important factor that affects the germination, vegetative, and reproductive growth of barley. The ideal temperature for barley germination and reproductive growth is 12–25 ˚C and 5–28 ˚C, respectively (Fettell et al., 2010). Temperatures outside the optimum range affect photosynthesis and the development of reproductive parts that contribute to yield quantity and quality reduction. The shortening of the growing period (i.e., the time from sowing to maturity) with increasing temperatures has been identified as the main yield-reducing factor in the current study, which is consistent with previous findings (Asseng et al., 2015; Porter et al., 2014). Araya et al. (2019) reported that an increase of air temperature by 2–8 ˚C significantly decreased the grain yield of barley by 6–11%. In a warmer climate, the growing period is shorter so there is less time to intercept light for photosynthesis, resulting in less biomass accumulation and lower yields. To adapt crops to a warmer climate, the growing period could be extended by delaying anthesis, and the selection of different cultivars with a longer vegetative phase is vital.

The genetic difference between the cultivars is one of the factors that could play a significant role in response to climate change. The effect of temperature on species could be cultivar-specific regarding timing, intensity, and duration of stress (Opole et al., 2018; Prasad & Maduraimuthu, 2014). Studies indicate that treatments and environmental interactions can have a substantial effect on yield differences among cultivars (Chala, 2021; Habte et al., 2020). In the current study, the yield reduction projected for cultivar EH-1493 (−19.7%) was lower than the reduction projected for cultivar Traveller (−44.4%) averaged across all study areas, models, and RCPs. In agreement, a study by Dobocha et al. (2020) recorded a significantly higher yield by cultivar EH-1493 compared with cultivar Traveller across different locations in Ethiopia. The mean yield at the study area for cultivar EH-1493 and Traveller are 4,300 and 3,000 kg ha^{-1}, respectively (Assefa et al., 2021; Niguse & Mulatu, 2018). In line with the current study, previous analysis of the climate-crop relationship showed that global warming can bring both positive and negative effects, but negative effects tend to dominate (Knox et al., 2012; Lobell & Field, 2007; Lobell et al., 2011; Schlenker & Lobell, 2010; Wang et al., 2008; You et al., 2009). The decrease in yield was mainly due to the acceleration of plant development that resulted from increased temperatures, although this response varied among the tested cultivars. Considerable crop production is projected, particularly in sub-Saharan Africa including Ethiopia (Akinseye, 2020; Kassie et al., 2014). Estimation of the effect of climate change could result in a 50% reduction in rainfed agricultural production in Africa (IPCC, 2014; Mbow et al., 2019; Ketiem et al., 2017). In addition, the report by the Intergovernmental Panel on Climate Change showed that an increase of temperature by 1–2 ˚C could likely have a negative effect on major cereal crops (IPCC, 2018). The report suggested that agricultural productivity decreased due to less favorable weather conditions, reduced water availability for irrigation, increased heat stress, and prolonged droughts.

4.3 | Climate change adaptation options

Adaptation strategies are expected to help in dealing with climate change to avoid or minimize the negative effects and exploit possible positive effects on crop production. Several agronomic adaptation strategies for agriculture, such as shifting sowing dates, varying sowing density, and fertilizer, have been suggested (Bryan et al., 2009; Travasso et al., 2006; Ngigi, 2009). In the present study, sowing dates, sowing densities, and fertilizer rates were simulated for two cultivars EH-1493 and Traveller under the future predicted climate conditions at four study areas. The trend of the adaptation options was similar between the cultivars and RCPs. However, a variation in the response of barley production to different adaptation strategies among the locations was observed. In general, the sensitivity analysis revealed that the effect of climate change on barley production at Holeta could be mitigated to a certain extent, and a higher yield gain was observed by applying different adaptation strategies. The reason why the adaptation strategies showed a better response at Holeta might be related to the lower baseline temperature by 2 ˚C compared with the other study areas. The average sowing date for the baseline climate was between 16–30 June. If the baseline sowing date is used for future climate scenarios, the yield will be affected negatively unless additional measures are taken. Barley yield increased up to 16% at Holeta under both RCPs within the early (1–15 June) sowing windows, and the negative effect of climate change was minimized at the other locations, according to the crop model estimates. In line with the current study, shifting the sowing date to compensate for climate change effects was proposed in the previous analysis (Sultana et al., 2009; Ahmad et al., 2015). The sowing date is generally determined by local agricultural climatic resources. Appropriate sowing dates can take full advantage of local ecological resources such as precipitation and light and avoid adverse conditions in the growing season (Cammarano et al., 2016).

In addition, optimizing sowing density is likely to improve crop canopy structure and distribution of light and heat resources (Casal et al., 1985). The recommended sowing density in Ethiopia is 165 plants m^{-2}. The current study projected that increasing the planting density by 25% would result in an increase of barley yield at Holeta and minimize the negative effect at the other locations under the future climate conditions, according to the crop model estimates. In addition, a positive response of yield in the future climate was projected at Holeta, with a 50% higher fertilizer rate than recommended. Further, the predicted negative effect of climate change on yield was reduced at the other study areas compared with the baseline. In line with the current study, previous studies reported that an increase in fertilizer application could help to mitigate the negative effect of climate change (Kassie et al., 2015; White et al., 2011). Generally, in the Ethiopian highlands, climate change may extend the agricultural growing seasons as a result of increased temperatures and rainfall changes (Thornton et al., 2011). Therefore, shifting the sowing period and increasing sowing density and fertilizer rate of barley from the baseline seems to be a promising adaptation strategy to increase food security in the face of expected climate change.

5 | CONCLUSION

Overall, the evaluated model in this study represented satisfactorily the yield of barley cultivars grown at the experimental sites in Ethiopia. The output of five global climate models under two representative concentration pathways (RCPs 4.5 and 8.5) indicated that the future climate will be warmer than the baseline (1980–2010) with reduced rainfall. As a result, a reduction of barley yield was observed when averaged across all climate scenarios and study areas. The highest reduction (98%) of barley yield was recorded for cultivar Traveller at Jimma, while a yield gain up to 15% was observed for cultivar EH-1493 at Holeta under the future climate. The sensitivity analysis indicated that early sowing and increased sowing density and fertilizer rate will contribute to lowering the effect of climate change but these practices have to be done and analyzed specifically for each location and cultivar. An early sowing window (1–15 June) indicated higher yields at Holeta and could potentially minimize the yield reduction at the other locations when also considering an increase up to 25% in sowing density and 50% higher fertilizer rate. Further studies on plant-environment-management interactions and adaptation strategies are needed to increase productivity in agriculture and improve food security in the future.

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AUTHOR CONTRIBUTIONS

Mekides Woldegiorgis Gardi: Conceptualization; Data curation; Formal analysis; Validation; Visualization; Writing – original draft; Writing – review & editing. Emir Memic: Formal analysis; Writing – review & editing. Eshetu Zewdu: Data curation; Formal analysis; Writing – review & editing. Simone Graeff-Hönninger: Conceptualization; Supervision; Writing – review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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6. General Discussion

The primary goal of this Ph.D. research was to gain a better understanding of the effects of climatic variability and change on cereal-based production in barley-producing locations of Ethiopia, as well as to investigate adaptation options to mitigate the given climate-related risks. The dissertation assessed and explored how existing climate variability affects crop production and how it might be affected by projected climate change, as well as current techniques and options for adapting to expected climate change. The study first synthesized and summarized the effects of eCO_2 and its interaction with different levels of temperature and nitrogen on barley production using a meta-analysis approach (Chapter 3) to improve the understanding of the interactions between climate and agricultural production. Further, the response of Ethiopian barley landraces and released cultivars to eCO_2 were evaluated and discussed in Chapter 4. Relevant agro-climatic variables were examined under current climate (baseline) and future climate change scenarios, and the implications for rainfed crop production were discussed. The study then quantified how current and projected climate variability affects barley productivity (Chapter 5) and investigated adaptation options. In the general discussion, the overall results of the thesis and its implication will be discussed. Detailed discussions of the results of the individual publications were already included within each chapter.

6.1. Ethiopian climate change and variability

Climate change and its variations are the most pressing challenges in developing countries, where their impact at the regional/sub-regional and ecosystem levels is likely to be uneven and unpredictable. Ethiopia, as part of the African continent, is subject to frequent and devastating climate extreme events, which can have negative economic and social consequences. In Chapter 5, historical trends, and projected climate changes in Ethiopian barley-growing locations (Assela, Ambo, Holetta, Jimma) were examined. Annual rainfall in the study locations showed mixed trends from 1981 to 2010, and the result was supported by reports from other regional and national studies. Some studies found decreasing trends in Ethiopia (Cheung et al., 2008), but others found no strong evidence for consistent changes in annual rainfall (Seleshi & Camberlin, 2006). During the period 1981-2010, seasonal rainfall (February-March) had a high inter-annual variability (CV=25.6-36.7%) (Table 1).

Table 1: Mean, coefficient of variation, and trend of historical minimum, maximum, temperature, and rainfall (1981-2010).

		Tmax[a]			Tmin[b]			Rainfall		
Location	Season	Mean	CV (%)	Trend	Mean	CV (%)	Trend	Mean	CV (%)	Trend
	Annual	26.0	1.7	0.8	10.6	6.8	1.5	1070.6	15.4	0.9
	FMAM[c]	28.0	2.2	0.2	11.5	6.8	1.3	231.2	36.7	-0.2
Ambo	JJAS[d]	23.7	3.1	0.4	10.8	8.2	1.9	714.2	23.6	0.2
	Annual	25.6	1.9	1.0	12.7	8.3	-0.9	963.6	12.2	-0.6
	FMAM	27.3	2.6	1.5	13.4	8.6	-1.5	359.0	34.6	-0.9
Assela	JJAS	24.5	2.3	0.0	13.2	8.3	-1.9	458.8	23.4	0.6
	Annual	26.4	1.9	0.5	13.9	7.6	-0.9	953.1	13.3	-1.1
	FMAM	27.3	2.6	1.4	14.4	8.0	-1.4	403.2	35.9	-1.1
Holeta	JJAS	25.4	2.2	0.3	14.3	7.7	-1.5	456.9	13.5	1.1
	Annual	31.0	1.3	1.6	17.1	6.9	1.3	1763.6	13.1	1.3
	FMAM	32.5	2.1	2.4	17.6	6.7	2.3	411.4	25.6	-0.5
Jima	JJAS	29.3	1.6	2.2	18.3	5.5	1.5	984.6	11.0	1.3

[a] maximum temperature; [b] minimum temperature; [c] February-March; [d] July-September

Future climate change scenarios based on five GCMs (ACCESS1-0, HadGEM2-ES, inmcm4, MPI-ESM-MR, and MRI-CGCM3) and two Representative Concentration Pathways (RCP4.5 and RCP8.5) that were available at the time of analysis suggested that annual rainfall could change by -61.4 to +86.1% in the future compared to the baseline period 1981-2010 (Chapter 5). The annual increase in rainfall was due to a significant increase during the months (November-January) that are less important for agriculture under current conditions. The majority of GCMs predicted a decrease in rainfall during the main growing season (June-September). Nonetheless, there is an ongoing debate about the high uncertainties in climate projections for the East African region, implying that most GCMs may be unable to capture the distinct effects of rapid warming in the Indian ocean on circulation and precipitation patterns (Funk et al., 2008). This phenomenon has resulted in suppressed convection over tropical eastern Africa in recent decades, reducing rainfall during March-June, a trend that is expected to continue for some time but is not or is poorly captured by most GCMs (Williams & Funk, 2011).

In terms of temperature, there is a clear indication of warming trends under current and future climate conditions. The maximum temperature in the study locations increased by 0.2-2.4 °C per decade, with an average increase of 1.3 °C between 1981 and 2010. The analysis of future climate change scenarios revealed that the mean temperature will continue to rise by 1.6-3.3 °C in the 2050s and 1.8-4.1 °C in the 2080s (Chapter 5), which is consistent with other regional and global studies (Conway & Schipper, 2011). In terms of future changes, the entire continent of Africa is expected to warm throughout the century (Boko et al. 2007). Model-based predictions of future greenhouse gas-induced climate change for the continent indicated that this warming will continue, and in most scenarios, as reported in the current study, this warming will be exacerbated (van de Steeg et al., 2009). According to projected results, the average temperature will rise by the end of the century between 0.3 and 4°C by 2099, roughly 1.5 times the mean global temperature (Boko et al. 2007), with warming likely to be severe over the interior of semi-arid margins of the Sahara and Central Southern Africa (Eriksen et al., 2008). By 2100, the temperature in SSA is expected to rise by 2.0 to 4.5 °C, which is higher than the global average (Müller, 2009).

Natural disasters in many parts of SSA involve either too much or too little rain (Brown and Crawford 2009). Elevated temperatures and unpredictability of rainfall (both temporally and spatially) are expected to increase the frequency and intensity of extreme weather events in the SSA, such as droughts, heavy rainstorms, flooding, and forest fires events (Case 2006). Droughts and floods, for example, have been widespread in most of SSA, particularly in the Horn of Africa and the Sahel. One-third of Africa's population lives in drought-prone locations and is vulnerable to its consequences (World Water Forum 2000). Droughts have primarily persisted in the Sahel, the Horn of Africa, and southern Africa since the 1960s, capturing the attention of several researchers (e.g. Usman and Reason 2004; Mortimore 1989, Mortimore and Adams 2001; Brooks 2004; Orindi et al. 2007; Zeng 2003). As a result of failed annual rains in the 1990s and 2000s, several East African countries, including Ethiopia, Kenya, and Somaliland, experienced severe droughts. Many people have been left without enough food to eat because crops have been unable to grow (Orindi et al. 2007). On the other hand, some SSA countries have received excessive rainfall. Burkina Faso (2007 and 2009), Mozambique (2000 and 2001), some parts of Ethiopia (2006), and Ghana (2007 and 2010), have all experienced severe flooding with severe economic consequences.

As a result of climate change, Cline (2007) predicted a generally significant reduction in overall yields across SSA based on a synthesis of results from various global circulation and Ricardian models. Also using GCMs, Parry et al. (1999) discovered that by 2080, Africa is expected to experience significant yield reductions, production decreases, and increases in the risk of hunger due to climate change. Crop yields in Africa may fall by 10–20% by 2050 because of warming and drying, but there are places where yield losses may be much higher, as well as places where crop yields may increase, such as some parts of the Ethiopian highlands, where maize production is expected to benefit from potential climate change

(Jones and Thornton 2003). Yield reductions of up to 50% are projected in some regions by 2050, and crop net revenues of up to 90% by 2100 in South Africa, with small-scale farmers being the most affected (Boko et al. 2007). According to the International Food Policy Research Institute's (IFPRI) model, average rice, wheat, and maize yields will decline by up to 14, 22, and 5%, respectively, due to climate change in 2050 (IFPRI 2009). A panel analysis of historical crop production and weather data estimated that by mid-century, the mean estimates of aggregate production will reduce for maize, sorghum, millet, groundnut, and cassava, respectively, by 22, 17, 17, 18, and 8% (Schlenker and Lobell 2010).

A modelling study indicated that total cropland in Africa may not change much as climate change alters agroecological zones (AZEs) and farm productivity within them Kurukulasuriya and Mendelsohn (2008a). The shifting of AZEs is expected to increase cropping locations in the middle to high elevations. Cropland is expected to be lost in the desert and lowland semiarid AZEs. Kurukulasuriya and Mendelsohn (2007) discovered that net revenues fall as precipitation falls or temperatures rise across all surveyed farms using the Ricardian method and farm-level data from over 9,000 farmers in 11 SSA countries. A 10% increase in temperature, for example, would result in a 13% decrease in net revenue. The net revenue elasticity concerning precipitation is 0.4. With over 9,500 farmers and by 2100, Kurukulasuriya and Mendelsohn, 2008b) discovered that if future warming is mild and wet, dryland crop net revenues could increase by 51%, but fall by 43% if future climates are hot and dry. Adejuwon (2006) modeled the worst-case climate change scenarios for maize, sorghum, rice, millet, and cassava in Nigeria and projected that, in general, crop yield will increase across all low land ecological zones as the climate changes during the early parts of the twenty-first century, but the rate of increase will be slow towards the end of the century. Gbetibouo and Hassan (2005) discovered in South Africa that increasing temperature has a positive effect on the net revenue of certain field crops (including maize, wheat, sorghum, sugarcane, groundnut, sunflower, and soybean), whereas decreasing rainfall has a negative effect on these crops.

Climate change affects the suitability of areas to produce a specific crop in addition to weather influence on crop yields and projected yield losses due to climate change. Crop suitability modeling results show that the suitability of areas to produce maize, teff, sorghum, and wheat in Ethiopia varies across different AZEs (Murken & Gornott, 2020). The study concluded that the areas shares suitable for producing sorghum are highest in all AZEs, with the suitability for wheat production lowest at a national level, but this varies across AZEs and administrative regions. Under the current climatic condition, 49% of Ethiopia has potential for maize production while, 38% of the country is suitable for successful teff production, 53% for sorghum and 31% of the country is suitable for wheat under current conditions. By 2050, the model projects a net loss in maize suitability of 5% under RCP2.6 and 7% under RCP8.5 for the whole of Ethiopia. Amhara and Tigray will experience lower suitability, with a suitability increase in South Nation Nationality and People (SNNP). The model projects a net loss in teff suitability in Ethiopia of 4% under RCP2.6 and 7% under RCP8.5 by 2050. Sorghum suitability is projected to rise with climate change: At the national level, models project a net increase in sorghum suitability of 5% under RCP2.6 and 2% under RCP8.5 by mid-century. Out of the four crops analyzed, wheat will be most affected by climate change. Its net suitability is projected to decrease by 9 and 12% under RCP2.6 and 8.5, respectively until 2050 (Murken & Gornott, 2020).

6.2. Climate change effects on barley production

Climate variability and change are two of the most crucial issues confronting agricultural production. Of course, the actual effects of climate variability on agricultural systems vary depending on location and adaptive capacity (Vermeulen et al., 2013). Increasing CO_2, inter-annual variability of rainfall associated with intermittent dry spells during crop growing seasons, and rising temperature all have an impact on crop production in different ways. Elevated CO_2 promotes plant growth (productivity and total biomass) by increasing net CO_2 assimilation rate (A) and improving water use efficiency (WUE) in C_3 plants (e.g., barley, rice, and wheat) through reduced stomatal conductance (gs) and transpiration, resulting in higher yield (Broberg et al., 2019; Drake et al., 1997; Long et al., 2006; Mitterbauer et al., 2017; Schapendonk et al., 2000). In general, an increase in barley yield, primarily in vegetative biomass, number of grains, and grain yield, was observed in the current study using eCO_2 as a single factor (Chapters 3 and 4). The response of barley was observed to increase as the level of eCO_2 increased. For instance, grain yield and number of grains were significantly increased for eCO_2 between 651 and 720 ppm compared to lower levels of CO_2 concentrations (Chapter 3). Similar studies that used a meta-analysis technique to summarize eCO_2 experiments with different crops concluded that eCO_2 generally increased yield by increasing panicle and grain numbers (Pincebourde & Woods, 2012). In addition, the results from a climate chamber experiment with 30 Ethiopian barley cultivars confirmed that eCO_2 significantly increased plant height, aboveground biomass, grain yield components, and water use efficiency (Chapter 4). The response in yield parameters to eCO_2 is comparable to previous enclosure studies (Alemayehu et al., 2014; Clausen et al., 2011; Kimball, 1983) and

FACE study on barley (Weigel & Manderscheid, 2012).

The annual variability of crop yield was found to be strongly correlated with climate variability, particularly rainfall within and between seasons, which is a common problem of production uncertainty in most rainfed farming systems in Sub-Saharan Africa (Cooper & Coe, 2011; Müller et al., 2011). In Chapter 5, the effects of various climate change scenarios on Ethiopian barley production were examined. The results showed that due to predicted climate change in the 2050s, barley yield response ranged from +3 to -98% across climate change scenarios compared to the baseline (1981-2010). Under future climate change scenarios, the main yield-limiting factors are rising temperatures up to 2.6 °C in the 2050s and up to 4.6 °C in the 2080s during the growing season combined with a decrease in seasonal rainfall, resulting in an overall shorter growing season. Under climate change scenarios, the impact of temperature increases is greater than that of rainfall, as evidenced by the fact that barley yield decreased for scenarios that predicted an increase in growing season temperature. The findings in Chapter 5 imply that, if things continue as they are, progressive climate change will have a negative impact on crop productivity in Ethiopia. Several global and regional studies have also warned that climate change may have a negative impact on agricultural productivity in most parts of the world, particularly in Sub-Saharan Africa (Cairns et al., 2013; Müller, 2013), highlighting agricultural adaptation and risk management strategies.

Another important factor to consider is the impact of climate change on grain quality, which was not addressed in the present thesis. While crop breeding is already heavily focused on yield traits, grain quality traits have received relatively little attention. This is a major concern because, as discussed further below, environmental stress will affect the relative abundance of starch, protein, and minerals (Loladze, 2014; Ziska et al. 2012; Goicoechea et al 2016)

Starch is the most abundant end product of cereal growth and development, accounting for roughly 70% of grain dry weight (w/w) (Jung et al. 2008). As eCO_2 speeds up photosynthetic rates in C3 plants, increased carbohydrate translocation from the source (leaves and stems) to the sink (grains) is expected to boost grain starch content (Thitisaksakul et al. 2012). Worch et al. (2011) discovered that changes in endosperm starch content were positively correlated with grain yield and concluded that grain starch content is one of the leading causes of yield loss in drought-stressed crops. This could be due to a lack of water, which would impair both the production of photo-assimilates (a source of carbon skeletons for starch synthesis) and the activity of enzymes involved in starch biosynthesis in the endosperm. As a result, the lower starch content observed in grains of genotypes subjected to water deficit may be related to the availability of reducing sugars (Avila et al. 2017). Increasing temperatures also have a negative impact on grain starch concentration. The reduction in starch concentration under high-temperature conditions has been attributed to two factors: (i) a shorter grain-filling period, which may reduce the duration of starch accumulation, and (ii) impairment of starch metabolism (Altenbach et al. 2003)**.** Hawker and Jenner (1993) and Keeling et al. (1993) reported that high temperature (generally around 30 ºC) inhibited starch metabolism, possibly due to thermal denaturation negatively affecting the activity of starch synthase.

Elevated CO_2 has been shown to reduce grain protein (or N) content in edible crop parts (Loladze, 2002; Taub et al. 2008; Medek et al. 2017). This decrease has been linked to increased photosynthesis and grain carbohydrate accumulation, resulting in lower grain protein levels due to a dilution effect (Högy et al. 2009; Chaturvedi et al. 2017). In addition, reduced protein concentrations in cereal grains under eCO_2 could be attributed to lower leaf protein concentrations in photosynthetic tissues, resulting in lower seed protein (Fangmeier et al. 1999; Fangmeier et al. 2000). On the other hand, high temperatures, in contrast to eCO_2, increased grain protein concentration by 10.4%, which could be attributed to greater remobilization of shoot-derived protein (Mariem et al. 2021). The grain protein concentration is expressed as a percentage of grain dry mass, which, along with the affected grains' smaller size and weight, would contribute to them having lower carbohydrate levels and, as a result, higher grain protein (Barnabas et al. 2008). Drought has an impact on plant phenology and physiology (Galle et al. 2009). Significant increases in grain total protein were found to be associated with low water availability. Drought stress, according to Bhullar and Jenner (1986), hinders the conversion of sucrose into starch during the grain-filling period but has a milder effect on protein biosynthesis. The fact that drought had no significant effect on grain starch concentration would rule out a lower carbohydrate level as a factor that induces increased grain protein content (Singh et al. 2012) discovered that, in addition to lower rates of carbohydrate accumulation in the grain of drought-stressed plants. The increased grain protein concentration during a drought could be explained by the shortened maturation time associated with stress conditions, which tends to prioritize protein accumulation over starch accumulation in cereal grains (Wang & Frei, 2011). Drought, among stresses, accelerates the movement of senescence-inducing resources (including amino acids) during grain filling, acids are transferred from the leaves to the seeds. Several studies have shown that reserve mobilization contributes more to final grain yield under stressful conditions than under relatively well-irrigated conditions (Blum, 1998; Yang et al. 2003; Srivastava et al. 2017).

Numerous studies found that eCO_2 causes macro/microelement depletion in grains, however, the magnitude of the reductions varies between minerals (Högy et al. 2009; Fernando et al. 2012; Zuh et al. 2018; Houshmandfar et al. 2015). According to the findings of Mariem et al. (2021), the concentrations of Zn, Fe, S, Ca, Mg, P, Mn, K, and Mo were significantly reduced. Such reductions have been linked to increased spikes and grain production, which results in a grain nutrient-dilution effect, lowering nutritional value. Furthermore, by decreasing transpiration (due to stomatal closure caused by long-term exposure to eCO_2, high CO_2 can reduce mass flow in the soil toward roots, reducing the availability of mobile minerals in the rhizosphere (Loladze, 2002). While carbohydrate dilution should reduce all other nutrients in plant tissues evenly (Gifford et al. 2000), the other effects of eCO_2 on plant physiology are not distributed evenly among the minerals. Reduced transpiration and increased biosynthesis, for example, have a greater impact on some minerals than others (Loladze, 2002). Indeed, a meta-analysis of over 7500 pairs of observations from eCO_2 studies revealed a significant reduction in foliar Mg, N, P, K, Ca, S, Fe, Zn, and Cu but not Mn content in C3 plants, with underlying biochemical mechanisms responsible for the increased Mn: Mg ratio proposed (Bloom and Lancaster, 2018).

Research has found that both heat and drought stress tends to increase mineral concentrations (including Fe, N, S, Zn, K, and P). The observed increase in grain protein and N concentrations with increasing temperature indicates that there is more N per unit of starch (Stone et al. 1997). Furthermore, Fe and Zn levels tend to rise during a drought. Ge et al. (2010) reported that soil drought stress improved transport mechanisms and/or routes for some minerals, such as Fe and Zn, leading to higher grain concentrations of these elements. Furthermore, according to other studies (Ge et al. 2010; Farahani et al 2010), the increase in Fe and Zn levels may be associated with more efficient remobilization of these nutrients from leaves to grains. Other authors concluded that an increase in Fe and Zn concentrations is related to sink strength at the single grain level (Miller et al. 1994) specifically observed in maize where the mineral content was higher in drought-sensitive genotypes (which produced fewer grains than tolerant genotypes) than in fully watered plants. According to this explanation, the increase in nutrient concentration in grains may be related to the number of grains formed, with each grain acting as a separate sink (Avila et al. 2017).

6.3. Future genetic resource identification and exploitation

Genotypic variation is important in determining crop physiological and yield responses to climate change. In the meta-analysis study (Chapter 3), genotypes with a high yield with different genotypic characteristics were discovered by comparing genotypes examined in previous experiments (Table 2). Similar research on wheat (Ziska et al., 2004) and rice (Wang et al., 2015) reported genetic variability in total biomass and grain yield response to eCO_2. The results of the meta-analysis study showed that modern genotypes have a higher positive response to eCO_2, but they do not always perform better than older genotypes. Previous research has found very little evidence that breeders inadvertently selected for increased CO_2 responsiveness, and several studies have found that older genotypes are more responsive to eCO_2 than modern genotypes (Ainsworth, 2008; Hay & Gilbert, 2001; Ziska et al., 2012).

Table 2: Best responding genotypes to eCO_2, their description, yield attributes, and % change at eCO_2.

Genotype	Genotype description	Yield attributes	% Change in eCO_2
Anakin	Modern spring barley cultivar	Vegetative biomass	+53.3
Bambina	Mid-maturing spring cultivar	Number of grains	+57.2
		Harvest index	+30.3
Golden promise	High yielding, short height, and early maturing	Number of grains	+49.0
		Harvest index	+39.1
Atem	European modern spring cultivar, drought tolerant	Grain yield	+40.4
Alexis	Two-row German malting barley cultivar, heat tolerant	Grain yield	+38.7

A significant intraspecific variation between Ethiopian barley genotypes ranging from -25% to +122.3% in the landraces and -42% to +140.2% in released cultivars was observed in the response of grain yield under eCO_2 (Chapter 3). Comparing landraces and released cultivars as a group, the highest average percentage change due to eCO_2 was recorded for the released cultivars. Because the group of released cultivars showed a better increment in grain yield and yield components under eCO_2, one might assume that enhanced net-photosynthesis to eCO_2 was unintentionally targeted through breeding; however, the actual yield of landraces was higher than the released cultivars under both ambient and elevated CO_2 conditions (Figure 3). As a result, it appears worthwhile to look for genetic resources for future compounded environments among landraces as well as released cultivars. Under the eCO_2 condition, the landraces *Lan_15, Lan_8, Lan_1, Lan_9,* and *Lan 6* showed the highest yields, while *Rel_4, Rel_5, Rel_6, Rel_7,* and *Rel_10* were among the released cultivars those with the highest yields. On the other hand, eCO_2 reduces ' vegetative biomass and grain yield in some barley genotypes. This could be related to changes in the shoot: root carbon allocation. Genotypes with negative vegetative biomass accumulation in the presence of eCO_2 were given newly assimilated carbon, but this would preferentially accumulate below ground for enhanced root system development (Mitterbauer et al. 2017). According to the findings of the current studies, breeding for eCO_2 exploitation could improve future crop production. Despite the overall positive correlation of genotypes/cultivars, high-yielding genotypes in aCO_2 may not always be high yielding in eCO_2, necessitating direct selection in eCO_2 to identify high-yielding varieties for future climates.

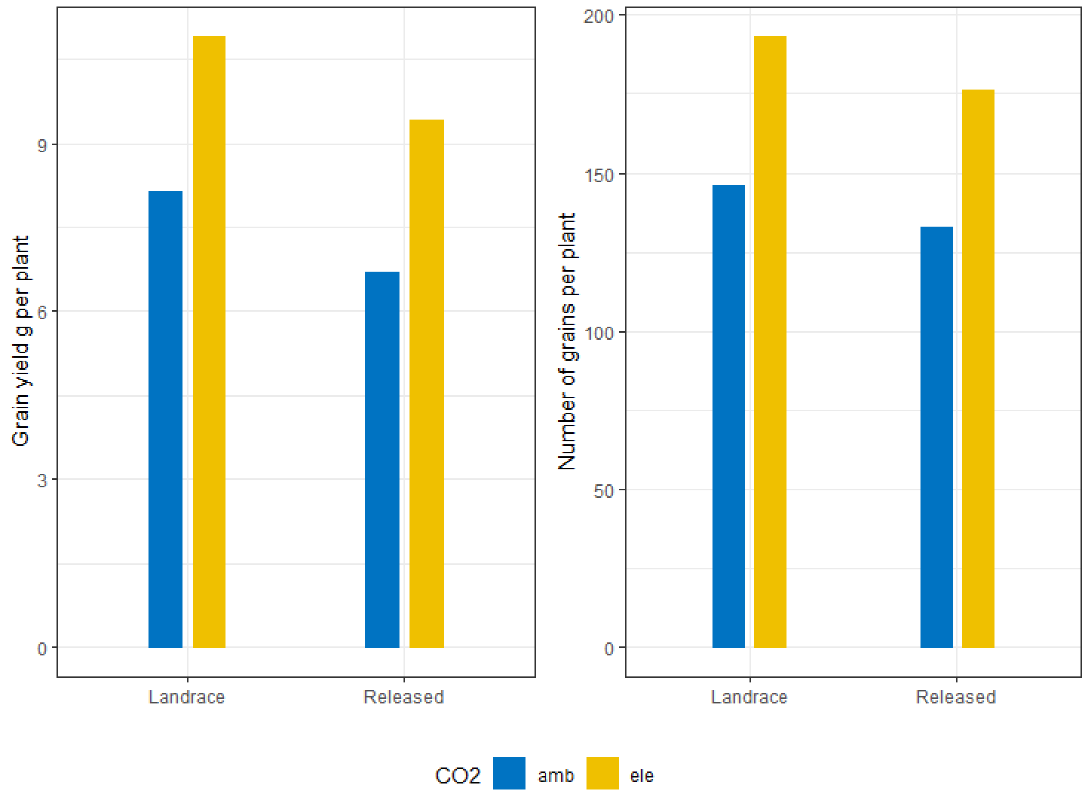

Figure 5: Mean response of landraces and released cultivars, (a) grain yield [g], and (b) number of grains per plant under ambient and elevated CO_2.

Because climate change is unpredictable, one of the most important characteristics is stay-green (SG). It is a secondary trait that allows crop plants to keep their green leaves and photosynthesis capacity for a longer period after anthesis, particularly in drought and heat stress conditions. SG was frequently reported for leaf greenness, while other organ contributions were detected. According to CO_2 estimates, the spikes' contribution to grain yield can reach up to 70% depending on the conditions in stressed wheat and barley (Maydup et al. 2010). Vaezi1 et al. (2010) discovered that the highest-yielding genotype of 11 barley genotypes tested under drought stress possesses SG characteristics. As a result, they proposed that increasing plant photosynthetic capacity and assimilating production during the later stages of grain filling can improve potential grain yield. Seiler et al. (2014) studied several barley lines with senescence or the SG phenotype and found that the SG lines performed better under drought conditions. Shirdelmoghanloo et al. (2019) investigated genetic variation for grain growth components, grain plumpness, and SG traits in 157 barley genotypes exposed to heat stress in two environments with three sowing dates. Their findings revealed a significant positive correlation between the SG and the grain filling duration, implying that SG plays a role in the stabilization of the grain filling duration in barley under heat stress. Furthermore, the possibility of developing heat-tolerant barley genotypes by focusing breeding programs on grain filling rate and SG traits was reported (Shirdelmoghanloo et al. 2019).

Furthermore, breeding for phenotypic plasticity in traits other than yield may provide resilience in an increasingly volatile environment (Shi et al. 2017). Breeding for plasticity in water use traits, for example, could result in improved survival and higher average yields (Huang et al. 2004). Similarly, novel approaches to identifying key environmental sensing genes in crop and model systems may provide an opportunity to breed phenotypic plasticity to build resilience in an increasingly variable environment (Huang et al. 2004). In addition, researchers have identified many more useful physio-morphological traits that influence drought and heat-stress tolerance to improve breeding efficiency in cereals, and these important traits for selection are summarized at different growth stages in Table 3.

Table 3: Physio-morphological traits that influence drought and heat-stress tolerance to improve breeding efficiency of cereals**.**

Growth stages	Physio-morphological traits
Germination and seedling stage	Seedling vigour, Ground cover, Coleoptile length, Root traits
Tillering and stem elongation stages	Seedling vigour, SPAD reading, NDVI, Leaf rolling, Leaf pubescence, Canopy temperature, Carbon isotope discrimination
Heading and anthesis	Days to heading and anthesis, SPAD reading, Waviness, Leaf rolling, Canopy temperature, Root traits
Grain filling	Flag leaf senescence, SPAD reading, NDVI, Canopy temperature, Awn length, Plant height

SPAD: Soil plant analysis and development; NDVI: normalized difference vegetative index

The simulation results of the CERES-Barley model for two Ethiopian barley cultivars also revealed a genotypic variation in the response of barley to the current and future climate conditions in Ethiopia. A reduction of yield on average under the future climate condition was recorded for the two cultivars, while variation was observed on the extent of the impact. For instance, cv. *EH-1493* in Holeta, showed a mixed trend ranging from a 14.7% increase to a 63% decrease in grain yield under future climate conditions (Chapter 5). On the other hand, cv. *Traveller* showed reductions of grain yield up to 98% under the two RCPs and in all locations. Bothe cv. *EH-1493* and *Traveller* have released cultivars for highland locations in Ethiopia. The mean yield at the study locations for cv. *EH-1493* and *Traveller* are 4300 and 3000 kg ha^{-1}, respectively on average under the current conditions (Assefa et al. 2021; Niguse 2018). Cv. *EH-1493* is food barley, which is characterized by high spike length, number of grains per ear, grain yield, harvest index, and hectoliter weight. Cv. *Traveller* is malt barley which is characterized by low protein content and medium grain yield.

The overall result of the current study indicated that future climate change will have a negative impact on cereal crop production and net revenue from the crop. Previous studies on the impact of climate change on cereal crops (wheat, rice, barley, maize, millet, sorghum, groundnuts, cassava, rye, and oats) indicated that climate change plays an important role in the diets of people in SAA (Schlenker & Lobell, 2010). Cereals account for 47% of total caloric food consumption (Kcal/capita/day) for SSA households and 50% of protein consumption. These grains are also an important source of expenditure, calories, and earnings for many poor people in developing countries, including those in SSA (Cranfield et al. 2003; Thurlow and Wobst 2003; Ulimengu et al. 2009). Thus, identifying high-yielding genotypes with better nutritious quality and exploitation of the genetic resources through breeding is essential for securing future food security.

6.4. Potential climate change adaptation options

Adapting agriculture to climate variability and change refers to the breeding of new cultivars to changes in management strategies in response to actual or anticipated climatic conditions or their consequences, to reduce risks or capitalize on opportunities (Adger et al., 2005). Crop model-based assessment of adaptation options under future climate change scenarios (Chapter 5) revealed that increasing fertilizer input levels, shifting sowing dates, and managing sowing densities would reduce the likely negative effects of climate change. The effect of different adaptation options showed a similar trend among the genotypes under all climate scenarios in the current study. However, the response of barley to various adaptation options varied across the locations. The summary of possible successful adaptation options for each location is presented in Table 4.

Table 4: Historical annual rainfall (mm), mean temperature (℃), and summary of best adaption options by location.

			Adaptation options		
Location	Rainfall (mm)	Temperature (℃)	Sowing window	Sowing density	Fertilizer application
Ambo	854.17	16.7	Normal	High	High
Asella	1106.3	18.4	Late	High	High
Holeta	1331.1	14.4	Late	High	High
Jimma	1628.5	19.3	Early	Normal	High

The simulation result for Jimma indicated that increasing fertilization might reduce the projected negative impact of climate change like in the other study locations. The highest yield reduction up to -31% for Jimma was recorded under RCPs end-century. Unlike the previous study locations, barley yield in Holeta is expected to mostly benefit from the future climate. The largest yield increases (up to +16%) were expected in the end-century under both RCP8.5, for high fertilizer application. In addition, an increase in barley yield under all climate change scenarios was observed in Holeta with early planting up to +14%. The largest yield decreases (up to -28%) were projected under RCP4.5 by the end of the century with lower fertilization than the recommended. The findings from the current crop-climate modeling study indicated that crop management adaptations might help to mitigate and even increase crop productivity in future changing climatic conditions. However, there is still a limitation of studies and projections of crop yields in Ethiopia under climate change. The current study lacks information on the possible impact of combined adaptation options for barley production, which needs to be investigated in future studies.

Coping with climate warming is an urgent concern globally and to adapt cereals to changing climatic conditions, considering multiple and diversified approaches is mandatory. Supplemental irrigation is one of the important adaptation strategies for reducing the harmful effects of climate change on cereal crops around the world (Rio et al. 2018). Supplemental irrigation is the application of a limited amount of water at critical stages of cereal crop growth and development when rainfall is insufficient to provide adequate water for proper growth and development. Supplemental irrigation can help to mitigate the effects of heat stress (Muluneh et al. 2016). During previous decades, canal irrigation water was the primary source of water; however, due to severe water shortages today, supplemental irrigation can be beneficial, particularly in arid environments. Supplemental irrigation, particularly during critical crop phenological stages and phases, has been shown to improve cereal crop yield and water efficiency in cereal-based cropping systems (Ndhleve et al. 2017). Supplementary irrigation is a simple, yet extremely effective practice that allows farmers to grow and manage cereal crops by irrigating at the optimal time, rather than being at the mercy of unpredictable precipitation. Supplemental irrigation allows farmers to grow cereal crops during their optimal growing season, which can increase grain yield while avoiding crop exposure to lethal heat and drought stresses in warm locations and frost in cooler locations around the world (Bigelow & Zhang, 2018).

Furthermore, agricultural biodiversity is critical for climate change adaptation (e.g., multiple cropping vs. sole cropping; diversified/integrated farming vs. specialized farming). Growing different crop varieties can help to reduce the risk of climate change (Smit & Skinner, 2002; Liu et al. 2018). Crop rotations will need to be more diverse and longer-cycled, combining sequences of annual row crops like maize and soybean with close-drilled cereals, shallow-rooted with deep-rooted crops, summer crops with winter crops, and annuals with perennials in the same fields (Bryan et al. 2009; Wognaa & Babu, 2020; Kumar et al. 2020). Similarly, increasing crop diversity may be a powerful way to reduce agricultural declines caused by climate change, as Morales-Castilla et al. (2020) concluded. Crop rotation and multi-cropping systems (including leguminous or green manuring crops in existing cereal-based cropping systems) can help to mitigate the negative effects of climate change.

Intercropping, with the creative arrangement of multiple interacting crop species to diversify the field and the landscape, will also benefit resilience to unpredictable weather (Gahlaut et al. 2020; Nelson et al. 2009; Olesen et al. 2011). According to Sloat et al. (2020), the warming effect on maize, wheat, and rice could be mitigated by crop migration over time and irrigation expansion. Multiple-cropping systems and strategies for integrating animals and crops will make better use of natural resources and applied inputs; these include permaculture, agroforestry, alley cropping, intercropping, and sowing C4 crops rather than C3 crops. Diverse cropping systems with spatial diversity that are tailored to specific fields, soil conditions, and unique agro-ecozones can help to mitigate the negative effects of heat stress (Mertz et al. 2009; Challinor et al. 2014). Sufficient cropping systems are promoted as an important approach to adaptation, particularly in regions that are heavily influenced by the effects of climate change. Grain yields in sequential cropping systems were higher than average grain yields in single cropping systems, implying that sequential cropping systems helped to mitigate the negative effects of climate change (Reidsma et al. 2010; 2015; 2018). Adopting advanced production technologies, physiologically based resilience to climate change, crop rotations, improved water and nitrogen use efficiencies, crop modeling, and planning ahead of time through the use of forecasting skills will help to adapt Ethiopian cropping systems to climate change under current and future climate scenarios (Aslam et al. 2017; Ahmed et al. 2016; Ahmed & Stockle, 2016; Tariq et al. 2020).

6.5. Impact of climate change on food security and economy of Sub-Saharan Africa

Cereals are an important food source for human consumption and food security (FAO, 2014), and SSA cropping systems among rural subsistence farms are largely cereal-based. The most widely cultivated cereal crops in SSA are maize, sorghum, millet, rice, wheat, barley, oats, buckwheat, and teff (Edmonds et al. 2009; Haque et al. 1986, World Bank, 2008). Sub-Saharan Africa’s rural economy remains strongly agro-based relative to other regions (Livingston et al. 2011). As such, economic growth focused on agriculture has a disproportionately positive impact on reducing food insecurity. In SSA, cereals are a staple food for, and mostly produced by, resource-poor farmers. Cereals and cereal products are an important source of energy, carbohydrate, protein, and fiber, as well as containing a range of micronutrients such as vitamin E, some of the B vitamins, magnesium, and zinc (McKevith 2004). Land under cereal production in SSA in 2008 was 92.132.298 hectares (World Bank, 2008).

Food security is defined as having physical, social, and economic access to sufficient, safe, and nutritious food that always meets their food preferences and dietary needs for an active and healthy life (FAO, 1996). Food security is commonly defined as three pillars: food availability, food access, food utilization, and food stability (FAO, 2000; Ericksen et al. 2010). Crop production and food production indices, livestock ownership indices, and national food balance sheets are all used to measure food availability (Renzaho & Mellor, 2010). Food accessibility is defined as the availability of resources such legal, political, economic, and social resources that an individual requires to access food. Food utilization refers to the use of food in sufficient quantities through an adequate diet, clean water, sanitation, and healthcare to achieve a state of nutritional well-being in which all physiological needs are met. Food utilization is defined as “the nutritional value of the diet, including its composition and methods of preparation; the social values of foods, which dictate what types of food should be served and eaten at different times of the year and on different occasions; and the quality and safety of the food supply, which can cause a nutrient loss in the food and the spread of food-borne diseases if not of sufficient standard (FAO, 2008). Food stability means that a population, household, or individual must always have access to adequate food. As a result, the concept of stability refers to the availability, access, and utilization dimensions of food security.

All aspects of food security are thus inextricably linked to agricultural production, which serves as both a source of food and a source of income for rural households. Food security vulnerability to climate change refers to the food system's proclivity to fail to deliver food security outcomes in the face of climate change, which includes environmental, economic, and social dimensions (FAO, 2016; Turral et al. 2011; Jodie et al. 2009; Thompson & Scoones, 2009; Hope, 2009). Climate change is exacerbating Sub-Saharan Africa's already significant inequalities. Almost half of the population is impoverished and relies on weather-sensitive activities. Urban poverty is becoming more prevalent and rapid urbanization is likely as rural populations, unable to cope with weather shocks, migrate to cities (often crossing borders) in search of work and shelter, as seen in the Sahel. Sub-Saharan African cities, on the other hand, are struggling to accommodate already high population densities and build more climate-resilient infrastructure. These challenges will be exacerbated by the region's rapid population growth. Conflicts sparked by these developments would stifle growth and increase inequalities (Burke and others 2009; Hsiang, Meng, and Cane 2011). Unless collective actions are taken regarding adaptation and mitigation of climate change's impact on food security and the economy of Sub-Saharan Africa, the region might face the worst-case scenarios.

6.6. Outlook for future research

With the objective of evaluating the response of barley to climate change and determining traits that contribute to yield changes, different approaches were applied. The following conclusions can be drawn from the study and make a significant contribution to barley production and breeding programs specifically in Ethiopia:

- The output of five global circulation models under two Representative Concentration Pathways (RCP 4.5 and 8.5) indicated that the future climate will be warmer than the baseline (1980-2010) with reduced rainfall.
- Elevated CO_2 is beneficial to barley growth when yield is considered as a single factor. Grain yields were much more responsive to eCO_2, due to an increase in ear biomass and grain number.
- However, a reduction in barley yield under future climate change scenarios was observed because of increasing temperatures and reduced rainfall in different parts of Ethiopia.

- A wide range of intraspecific variation was observed in the response of vegetative biomass and yield traits between genotypes. Thus, the identification of genotypes with higher grain numbers could improve the production of barley grain yield under future climate conditions.

Nevertheless, some gaps in the existing knowledge should be addressed in future research:

1. Experimental studies assessing crop production under multifactor climate conditions with superimposed variability should be encouraged to increase basic understanding and to identify genes and genotypes for future breeding programs when aiming to breed for a more resilient and high-yielding set of cultivars.
2. Food security involves more than production and it requires further attention to investigating the nutritional quality of barley genotypes under multifactor climate conditions with a set of landrace and cultivars.
3. Analyzing farmers' perceptions of climate variability and change, identifying current climate risk management strategies and barriers, and developing participatory plant breeding programs could all help to develop successful adaptation strategies.
4. Furthermore, cropping systems, and multiple adaptation options as a single and combined factor such as irrigation, intercropping, and shifting of crops should be simulated and analyzed under multifactor climate conditions in Sub-Saharan Africa.
5. Since climate change is an unpredictable, spatial and temporal distribution of crops and crop suitability assessment should be conducted and projected in future research.

7. Summary

Barley (*Hordeum vulgare* L.) is the fourth major cereal crop in the world, and it accounts for 8% of the total cereal production in Ethiopia based on cultivation location. Farmers may face unpredictable rainfall and drought stress patterns, such as terminal drought, in which rainfall ends before crops reach physiological maturity, posing a challenge to crop production. Furthermore, climate change is expected to reduce crop production/yield due to increases in carbon dioxide (CO_2) and ozone (O_3) concentrations, temperatures, and extreme climate events such as floods, storms, and heatwaves, highlighting the importance of taking action to develop climate-resilient cultivars and secure future crop production. Against this background, a meta-analysis study was conducted to synthesize and summarize to assess the overall effect of elevated CO_2 (eCO_2), and its interaction with nitrogen (N) and temperature on barley grain yield and yield components. A climate chamber experiment was carried out to identify the impacts of projected CO_2 enrichment (eCO_2) on a set of landraces and released cultivars of Ethiopian barley. The crop-climate modeling approach was used to simulate future climate change and to identify the impacts of climate change on selected barley genotypes and study locations in Ethiopia. Furthermore, adaption options were simulated and identified.

Publication I, aimed to answer how eCO_2 and its interaction with N and temperature affects barley yield at a global level. Peer-reviewed primary literature (published between 1991-2020) focusing on barley yield responses to eCO_2, temperature, and N were searched on different search engines. The response of five yield variables of barley was synthesized and summarized using a meta-analysis technique. Different experimental factors which might affect the estimation of the response of barley yield to eCO_2 were calculated. The results revealed that eCO_2 increased barley yield components such as vegetative biomass (23.8%), grain number (24.8%), and grain yield (27.4%) at a global level. Barley vegetative biomass and grain yield were increased under the combination of eCO_2 with the higher N level (151-200 kg ha^{-1}) compared to the lower levels. Grain number and grain yield were increased when eCO_2 combined with temperature level (21-25°C) this response was not evident. The response of barley to eCO_2 was different among genotypes and experimental conditions.

Publication II, the genetic diversity of Ethiopian barley was screened under eCO_2 enrichment in a controlled exposure experiment. The experiment was conducted at the Institute of Landscape and Plant Ecology, the University of Hohenheim in 2019. A total of 30 (15 landrace and 15 released cultivars) were grown under two levels of CO_2 concentration (400 and 550 ppm) in climate chambers. Plant-development-related measurements and water

consumption were recorded once a week and yield was measured at the final harvest. A significant increment in plant height by 9.5 and 6.7%, vegetative biomass by 7.6 and 9.4%, and grain yield by 34.1 and 40.6% in landraces and released cultivars, respectively were observed due to eCO_2. The effect of eCO_2 was genotype-dependent, for instance, the response of grain yield in landraces ranged from -25% to +122%, while it was between -42% to 140% in released cultivars. The water-use efficiency of vegetative biomass and grain yield significantly increased by 7.9 and 33.3% in landraces, with 9.5 and 42.9% improvement in released cultivars, respectively under eCO_2. Comparing the average response of landraces versus released Ethiopian barley cultivars, the highest percentage yield change due to eCO_2 was recorded for released cultivars. However, higher actual yields under both levels of CO_2 were observed for landraces.

Publication III, Current and future climate change, its impact on Ethiopian barley production, and adaptation options were simulated using the DSSAT-CERES-Barley model. Climate change scenarios were set up over 60 years using Representative Concentration Pathways (4.5 and 8.5), and five Global Climate Models. The changes in Ethiopian climate and barley production were calculated from the baseline period (1981-2010). Different sowing dates, sowing densities, and fertilizer levels were tested as climate change impact mitigation strategies in a sensitivity analysis. The analysis of a crop-climate model revealed an increasing trend of temperature (1.5 to 4.9 °C) and a mixed trend of rainfall (-61.4 to +86.1%) in the barley-producing locations of Ethiopia. The response of two Ethiopian barley cultivars was simulated under different climate change scenarios and a reduction of yield up to 98% was recorded for cv. *Traveler* while cv. *EH-1493* exhibited a reduction of up to 63%. Even though a similar trend was observed for most of the studied locations, cv. *EH-1493* showed a yield gain of up to 14.7% at Holeta. The sensitivity analysis on potential adaptation options indicated that the negative effects of climate change could be mitigated by earlier sowing dates, with a 25% higher sowing density and a 50% higher fertilizer rate than the current recommendation.

The results of the present dissertation show the change in the Ethiopian climate and its impact on barley production. Barley production could benefit from eCO_2; however, the response varied among genotypes, additional stress, and experimental condition. A reduction of barley grain yield under different climate change scenarios was observed mainly due to increasing temperature. However, the reduction could be minimized through different adaptation options. The information from the current dissertation could be used to identify agro-economic implications of CO_2 enrichment and climate variability on yield regarding appropriate

genotype selection and adaptation of regional cropping systems (e.g., management and breeding strategies). Further experimental studies assessing crop production, nutritional quality, and adaptation options under multifactor climate conditions should be carried out to increase basic understanding and identify genotypes for future breeding programs.

8. Zusammenfassung

Gerste (*Hordeum vulgare* L.) ist die viertwichtigste Getreideart der Welt und macht in Äthiopien, gemessen an der Anbaufläche, 8 % der gesamten Getreideproduktion aus. Die Landwirte sind möglicherweise mit unvorhersehbaren Niederschlägen und Trockenstressmustern konfrontiert, wie z. B. Dürre im Endstadium, bei der die Niederschläge aufhören, bevor die Pflanzen ihre physiologische Reife erreichen, was eine Herausforderung für die Pflanzenproduktion darstellt. Darüber hinaus wird erwartet, dass der Klimawandel die Pflanzenproduktion und erträge aufgrund des Anstiegs der Kohlendioxid (CO_2) und Ozonkonzentration (O_3), der Temperaturen und extremer Klimaereignisse wie Überschwemmungen, Stürme und Hitzewellen verringern wird. Vor diesem Hintergrund wurde eine Meta-Analyse durchgeführt, um die Gesamtwirkung von erhöhtem CO_2 (eCO_2) und dessen Wechselwirkung mit Stickstoff (N) und Temperatur auf den Ertrag und die Ertragskomponenten von Gerste zusammenzufassen und zu bewerten. Es wurde ein Klimakammerexperiment durchgeführt, um die Auswirkungen der prognostizierten CO_2-Anreicherung (eCO_2) auf eine Reihe von Landsorten und freigegebenen Sorten äthiopischer Gerste zu ermitteln. Der Ansatz der Kulturpflanzen-Klimamodellierung wurde verwendet, um den zukünftigen Klimawandel zu simulieren und die Auswirkungen des Klimawandels auf ausgewählte Gerstengenotypen und Studienstandorte in Äthiopien zu ermitteln. Darüber hinaus wurden Anpassungsmöglichkeiten simuliert und identifiziert.

In der **Publikation I**, wurde untersucht, wie eCO_2 und seine Wechselwirkung mit N und Temperatur den Gerstenertrag auf globaler Ebene beeinflussen. Es wurde in verschiedenen Suchmaschinen nach begutachteter Primärliteratur (veröffentlicht zwischen 1991-2020) gesucht, die sich mit den Auswirkungen von eCO_2, Temperatur und Stickstoff auf die Gerstenerträge befasst. Die Reaktionen von fünf Ertragsvariablen bei Gerste wurden mit Hilfe einer Meta-Analyse zusammengefasst und ausgewertet. Es wurden verschiedene experimentelle Faktoren berechnet, die die Schätzung der Reaktion des Gerstenertrags auf eCO_2 beeinflussen könnten. Die Ergebnisse zeigten, dass eCO_2 die Ertragskomponenten von Gerste wie vegetative Biomasse (23,8%), Kornzahl (24,8%) und Kornertrag (27,4%) auf globaler Ebene erhöhte. Die vegetative Biomasse und der Kornertrag der Gerste wurden durch die Kombination von eCO_2 mit einem höheren Stickstoffgehalt (151-200 kg ha^{-1}) im Vergleich zu den niedrigeren Werten gesteigert. Die Kornzahl und der Kornertrag nahmen zu, wenn eCO_2 mit dem Temperaturniveau (21-25°C) kombiniert wurde, wobei diese Reaktion nicht offensichtlich war. Die Reaktion der Gerste auf eCO_2 war je nach Genotyp und Versuchsbedingungen unterschiedlich.

Publikation II, Die genetische Vielfalt der äthiopischen Gerste wurde unter eCO_2-Anreicherung in einem kontrollierten Expositionsversuch untersucht. Das Experiment wurde im Institut für Landschafts- und Pflanzenökologie der Universität Hohenheim im Jahr 2019 durchgeführt. Insgesamt 30 (15 Landsorten und 15 freigesetzte Sorten) wurden unter zwei CO_2-Konzentrationen (400 und 550 ppm) in Klimakammern angebaut. Wöchentlich wurden pflanzenentwicklungsbezogene Messungen und der Wasserverbrauch aufgezeichnet und der Ertrag bei der Schlussernte gemessen. Eine signifikante Zunahme der Pflanzenhöhe um 9,5 bzw. 6,7 %, der vegetativen Biomasse um 7,6 bzw. 9,4 % und des Kornertrags um 34,1 bzw. 40,6 % bei den Landsorten und den freigesetzten Sorten wurde aufgrund von eCO_2 beobachtet. Die Auswirkung von eCO_2 war genotypabhängig, so reichte die Reaktion des Kornertrags bei Landsorten von -25% bis +122%, während sie bei freigegebenen Sorten zwischen -42% und +140% lag. Die Wassernutzungseffizienz der vegetativen Biomasse und des Kornertrags stieg bei den Landsorten signifikant um 7,9 bzw. 33,3 %, bei den freigesetzten Sorten um 9,5 bzw. 42,9 % unter eCO_2. Vergleicht man die durchschnittliche Reaktion von Landsorten und freigesetzten äthiopischen Gerstensorten, so wurde die höchste prozentuale Ertragsänderung aufgrund von eCO_2 bei den freigesetzten Sorten festgestellt. Allerdings wurden bei beiden CO_2-Konzentrationen höhere tatsächliche Erträge bei Landsorten beobachtet.

Publikation III, Der gegenwärtige und zukünftige Klimawandel, seine Auswirkungen auf die äthiopische Gerstenproduktion und Anpassungsmöglichkeiten wurden mit dem DSSAT-CERES-Barley-Modell simuliert. Es wurden Szenarien des Klimawandels über 60 Jahre mit repräsentativen Konzentrationspfaden (4.5 und 8.5) und fünf globalen Klimamodellen erstellt. Die Veränderungen des äthiopischen Klimas und der Gerstenproduktion wurden ausgehend von der Basisperiode (1981 - 2010) berechnet. In einer Sensitivitätsanalyse wurden verschiedene Aussaattermine, Aussaatdichten und Düngemittelmengen als Strategien zur Minderung der Auswirkungen des Klimawandels getestet. Die Analyse eines Kulturpflanzen-Klimamodells ergab einen steigenden Trend der Temperatur (1,5 bis 4,9 °C) und einen gemischten Trend der Niederschläge (-61,4 bis +86,1 %) in den Gerstenanbaugebieten Äthiopiens. Die Reaktion von zwei äthiopischen Gerstensorten wurde unter verschiedenen Szenarien des Klimawandels simuliert, und es wurde eine Ertragsminderung von bis zu 98 % für cv. *Traveler,* während cv. *EH-1493* einen Rückgang von bis zu 63 % aufwies. Obwohl für die meisten untersuchten Standorte ein ähnlicher Trend beobachtet wurde, zeigte cv. *EH-1493* in Holeta einen Ertragszuwachs von bis zu 14,7 %. Die Sensitivitätsanalyse zu möglichen Anpassungsoptionen ergab, dass die negativen Auswirkungen des Klimawandels durch frühere Aussaattermine, eine um 25 % höhere Aussaatdichte und eine um 50 % höhere Düngermenge als die derzeitige Empfehlung gemildert werden könnten.

Die Ergebnisse der vorliegenden Dissertation zeigen den Wandel des äthiopischen Klimas und seine Auswirkungen auf die Gerstenproduktion. Die Gerstenproduktion könnte von eCO_2 profitieren; die Reaktion war jedoch je nach Genotyp, zusätzlichem Stress und Versuchsbedingungen unterschiedlich. Eine Verringerung des Gerstenkornertrags unter verschiedenen Szenarien des Klimawandels wurde vor allem aufgrund der steigenden Temperatur beobachtet. Dieser Rückgang konnte jedoch durch verschiedene Anpassungsoptionen minimiert werden. Die Informationen könnten genutzt werden, um die agrarökonomischen Auswirkungen der CO_2-Anreicherung und der Klimavariabilität auf den Ertrag im Hinblick auf eine geeignete Genotypauswahl und die Anpassung regionaler Anbausysteme (z. B. Management- und Zuchtstrategien) zu ermitteln. Weitere experimentelle Studien zur Bewertung der Pflanzenproduktion, der Nährstoffqualität und der Anpassungsoptionen unter multifaktoriellen Klimabedingungen sollten durchgeführt werden, um das grundlegende Verständnis zu verbessern und Genotypen für künftige Züchtungsprogramme zu identifizieren.

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Declaration in lieu of an oath on independent work

according to Sec. 18(3) sentence 5 of the University of Hohenheim's Doctoral Regulations for the Faculties of Agricultural Sciences, Natural Sciences, and Business, Economics and Social Sciences

1. The dissertation submitted on the topic

Impact of climate change on future barley (Hordeum vulgare L.) production in Ethiopia

is work done independently by me.

2. I only used the sources and aids listed and did not make use of any impermissible assistance from third parties. In particular, I marked all content taken word-for-word or paraphrased from other works.

3. I did not use the assistance of a commercial doctoral placement or advising agency.

4. I am aware of the importance of the declaration in lieu of oath and the criminal consequences of false or incomplete declarations in lieu of oath.

I confirm that the declaration above is correct. I declare in lieu of oath that I have declared only the truth to the best of my knowledge and have not omitted anything.

Stuttgart,

Stuttgart, 10/03/22

Place, Date

Signature