EVALUATION OF CARBON STOCK UNDER MAJOR LAND USE/LAND COVER TYPES FOR DEVELOPING ALTERNATIVE LAND USE SCENARIOS FOR REDUCING GREENHOUSE GAS EMISSIONS IN HADES SUB-WATERSHED, EASTERN ETHIOPIA

By

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DECLARATION

I, Tessema Toru Demissie, declare that **"Evaluation of Carbon Stock Under Major Land Use/Land Cover Types for Developing Alternative Land Use Scenarios for Reducing Greenhouse Gas Emissions in Hades Sub-Watershed, Eastern Ethiopia**" is my own work and that all the sources that I have used or quoted have been indicated and acknowledged by means of complete references.

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This PhD Thesis has been submitted as the final copy with my approval as supervisor.

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Name Signature Date

DEDICATION

This dissertation work is dedicated to my wife Kalenesh Million for her concern, patience, and love.

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ACRONYMS AND ABBREVIATIONS

AFOLU	Agriculture, Forestry and Other Land Uses
AGB	Aboveground Biomass
ANOVA	Analysis of Variance
BD	Bulk Density
BHP	Beginning of Humid Period
BR	Beginning of Rain
CAF	Coffee Agro-Forestry
CEC	Cation Exchange Capacity
CL	Crop Land
DI	Deterioration Index
DJF	December-January-February
DWADO	Doba Woreda Agricultural and Rural Development Office
ECS	Estimates of the equilibrium Climate Sensitivity
EHP	End of Humid Period
EPA	Environmental Protection Authority of Ethiopia
ER	End of Rain
ET_o	Reference Crop Evapotranspiration
FAO	Food and Agriculture Organization of the United Nations
FMAM	February-March-April-May
GCM	General Circulation Model
GHG	Greenhouse Gas
GIS	Geographic Information System
GL	Grazing Land
GLM	Generalized Linear Model
GPS	Geographic Positioning System
ha	Hectare
IAMs	Integrated Assessment Models
IEA	International Energy Agency
IPCC	Inter-Governmental Panel for Climate Change
IUSS	International Union of Soil Science
JJA	June-July-August
JJAS	June-July-August-September
LC	Land Characteristics
LGP	Length of Growing Period
LQ	Land Quality
LSD	Least Significant Difference
LULCC	Land Use/Land Cover Change
LUR	Land Use Requirement
LUT	Land Utilization Type
MC	Mid-Century
MCE	Multi-Criteria Evaluation
MOA	Ministry of Agriculture (Ethiopia)
MWIE	Ministry of Water, Irrigation and Energy of Ethiopia
NC	Near-Century

ACRONYMS AND ABBREVIATIONS (Continued…)

NF	Natural Forest
NMSA	National Meteorological Service Agency of Ethiopia
NPP	Net Primary Production
NWRC	National Water Resources Commission of The Federal Ethiopian Government
OC	Organic Carbon
PAR	Photosynthetically Active Radiation
RCPs	Representative Concentration Pathways
RSG	Reference Soil Group
SD	Standard Deviation
SE	Standard Error
SMU	Soil Mapping Unit
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
SPSS	Statistical Package for Social Scientists
SRES	Special Report on Emission Scenario
TEB	Total Exchangeable Bases
TN	Total Nitrogen
t	tonne
UNFCCC	United Nations Framework Convention on Climate Change
WRB	World Reference Base for Soil Resources

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Evaluation of Carbon Stock Under Major Land Use/Land Cover Types for Developing Alternative Land Use Scenarios for Reducing Greenhouse Gas Emissions in Hades Sub-Watershed, Eastern Ethiopia

ABSTRACT

In the dominantly small-scale subsistence agricultural system of Ethiopia, where most of the organic inputs are not returned to soil and land is not used based on its best suitability, the contribution of agriculture to climate change mitigation/adaptation through reduction of greenhouse gases emission is undermined. When this low-input agricultural practice is coupled with rugged topography, high population pressure, generally low soil fertility, and looming climate change, ensuring food and nutrition security of society as well as sustainable use of land resources is practically impossible. Under such circumstances, finding alternative land uses, through scientific investigation, that meet the triple mandates of climate-smart agriculture under current and future climate is imperative. In view of this, a study was conducted in Hades Sub-watershed, eastern Ethiopia, to evaluate the carbon stock of major land uses, evaluate suitability of land for rainfed production of sorghum (*Sorghum bicolor* L.), Maize (*Zea mays* L.), coffee (*Coffea arabica*), upland rice (*Oryza sativa* L.) and finger millet *(Eleusine coracana* L.*)*, and project biomass production of late-maturing sorghum and maize varieties under changing climate and its contribution to carbon sequestration and reduction of greenhouse gases (GHGs) emission. Soil and vegetation samples were collected following recommended procedures. Secondary data on required crop parameters were collected for model calibration and validation in the biomass projection study made using the AquaCrop v6.0 model. Climate data of the study area was obtained from the National Meteorology Agency of Ethiopia and analyzed following standard procedures. Near-century (NC) (2017-2039) and Mid-century (MC) (2040-2069) climate was projected under two emission scenarios (RCP4.5 and RCP8.5) using four models (CNRM-CERFACS-CNRM-CM5, ICHEC-EC-Earth, MOHC-HadGEM2-ES, and MPI-M-MPI-ESM-LR) and a Multi-model Ensemble. Biomass production projection, for the climate projected under the two emission scenarios using the four models and the ensemble, was made for late-maturing sorghum (Muyira-1) and maize (BH661) varieties. From the projected biomass, organic carbon and its equivalent CO_2 were estimated. Furthermore, adaptation measures, involving adjusting planting dates and irrigation, under the changing climate were evaluated for their influence on biomass production under the time slices, RCPs, and models mentioned above. The carbon stock assessment study was conducted on four major land uses (cultivated, grazing, coffee agroforestry, and forest lands) identified in the study area. The land suitability assessment, using the maximum limitation method, study was conducted on four soil mapping units identified in the sub-watershed. Results indicate that total organic carbon stock (soil, litter plus live vegetation) in the sub-watershed ranged from 138.95 ton ha^{-1} in the crop land to 496.26 ton ha^{-1} in the natural forest. The soil organic carbon stock was found to be relatively higher than that of the vegetation carbon stock in the natural forest and coffee agroforestry land uses. The results of suitability evaluation revealed that the maximum current and potential (after corrective measures are taken) land suitability class for production of late-maturing sorghum (180-240 days cycle), maize (180-210 days crop cycle), finger millet (120 – 150 days cycle) and coffee in the sub-watershed is marginally suitable (S3c). The maximum current and potential land suitability for upland rice (120 days) is not suitable (N2c). The major permanent limiting factor is low mean temperature (14.6 °C) of the growing period in the study area as compared to the optimum temperature required for optimum growth of the selected crops. The major soil and landscape limitations include steep slope, poor drainage of low-lying areas, shallow effective root zone in the upper slopes, low organic matter and available P for sorghum and maize, high pH for maize and wetness for coffee. In all the climate models and emission scenarios, minimum and maximum temperature increment is high during June-July-August-September (JJAS) compared with the other seasons. The modest rise in minimum temperature and the slight increment of maximum temperature during the crop growing seasons (February-March-April-May (FMAM) and JJAS will benefit late-maturing sorghum and maize production in the study area. For the same model, the projected biomass yield and organic carbon sequestration of the two crop varieties varied with time slice and the type of emission scenario used. Generally, increasing biomass production and carbon sequestration were projected for Mid-century (MC) than Near-century (NC) for most of the models used. Late planting would increase sorghum biomass yield and the corresponding organic carbon as compared to early planting as projected by most of the models under both RCPs. Most models predicted an increase in maize biomass yield and organic carbon sequestration if supplementary irrigation is used. The results of this study indicate that the current land uses are not enhancing carbon sequestration because of their exploitative nature and the soil/landscape and climate are not optimum for production of the crops studied. The rise in temperature in the coming 50 years is expected to create a more favorable condition for production of late-maturing sorghum and maize varieties. In order to enhance carbon sequestration, soil productivity and crop yield, and reduce greenhouse gas emissions, the current land uses and their management require re-visiting.

Keywords: biomass yield, carbon dioxide equivalent, carbon sequestration, suitability evaluation, emission scenarios, mapping units, projection, suitability class

CHAPTER ONE

INTRODUCTION

1.1. Background

In the history of mankind, land has been playing a pivotal role through provision of essential goods and ecosystem services via its important processes, such as photosynthesis, since antiquity (Newbold *et al*., 2015; Isbell *et al*., 2017; Runting *et al*., 2017; Ziadat *et al*., 2017; Briassoulis, 2019; Kopittke *et al*., 2019). Recent literatures indicate that more than 70% of the ice-free land has been manipulated by human beings for supply of food, freshwater, and biodiversity (IPCC, 2018), among others. In addition to these, influence of land on the climate system through its role as a sink and source of carbon and its exchange with the atmosphere has been well documented (World Bank, 2012; Ciais *et al*., 2013; FAO and ITPS, 2015). Furthermore, IPCC (2018) pinpointed the key role that land use and its management play in influencing the terrestrial ecosystem and the global climate system. In connection with this, many recent studies reported that land use-related activities, such as deforestation, enteric fermentation, and application of fertilizers, are contributors of significant proportion of total anthropogenic greenhouse gases emissions (Ciais *et al*., 2013; Canadell and Schulze 2014; Smith *et al*., 2014; Tubiello *et al*., 2015; Zhu *et al*., 2016; Le Quere *et al*., 2018). Similarly, a rapid increase in methane and nitrous oxide emission from the agriculture sector, which solely depends on land, was reported (Tian *et al*., 2015; Hoesly *et al*., 2018; Wysocka-Czubaszek *et al*., 2018; Tian *et al*., 2019). IPCC (2018) emphasized the significant role land is playing in the exchange of energy, aerosols, and water between its surface and the overlying atmosphere.

However, this important resource is becoming increasingly vulnerable to climate change and extremes due to various drivers (Quan and Dyer, 2008; Ingram and Hong, 2011; Kumar and Das, 2014; IPCC, 2018; Muloo *et al*., 2019). Land degradation is often quoted as one of the most important drivers that cause unprecedented decline in land productivity and loss of other ecosystem services and biodiversity (Jolejole-Foreman *et al*., 2012; Gashaw *et al*., 2014; FAO and ITPS, 2015; Mirzabaev *et al*., 2015; Cerretelli *et al*., 2018; IPBES, 2018; Briassoulis, 2019; Muloo *et al*., 2019). As a case in point, FAO and ITPS (2015) identified ten threats that affect soil functions, including soil erosion, nutrient imbalance, soil acidification, soil organic carbon

(SOC) loss, waterlogging, salinization, soil contamination, soil compaction, soil sealing, and loss of soil biodiversity. Alarming population growth and land uses that are not compatible with land's capability, in combination with unfavorable climatic factors are exacerbating land degradation (Abu Hammad and Tumeizi, 2012; Field *et al*., 2014; Gashaw *et al*., 2014; Messina *et al*., 2014: FAO and ITPS, 2015; Nigussie *et al*., 2015; Hurni *et al*., 2016; Mekonnen *et al*., 2017; Ferreira *et al*., 2018). According to projection made by the United Nations (2018), the world population will increase to about 9.8 (± 1) billion people by 2050, peaking to a further 11.2 billion by 2100. This increase in population has resulted in increases in per capita consumption of food, feed, fiber, timber, and energy, which in turn have caused high rates of land and water use. Furthermore, a growing global middle class (Crist *et al*., 2017, cited in IPCC, 2018) economic growth and continued urbanization (Jiang and O'Neill 2017) have further intensified the pressure on land resources such as soils (Kopittke *et al*., 2019). This increased pressure on land, particularly through agriculture, has resulted in increasing greenhouse gases emissions, degradation of natural resources, and loss of biodiversity (FAO and ITPS, 2015; IPCC, 2018; Kopittke *et al*., 2019). Gibbs and Salmon (2015) made global estimate of total land degraded, excluding desert areas, as ranging from less than 10 to more than 60 million km^2. This unprecedented increase in land degradation is undermining the land's ability to serve as a sink, while intensifying greenhouse gases emissions. IPCC (2018) identified fighting land degradation through sustainable land management as one core strategy to overcome the negative impacts of climate change on ecosystems and societies.

Increase in greenhouse gases from different sources has been reported in different studies (e.g., Tubiello *et al*., 2013; IPCC, 2014; Federici *et al*., 2015; Tubiello *et al*., 2015; Rossi *et al*., 2016; IPCC, 2018; Le Quere *et al*., 2018). Most of these reports identified burning fossil fuel for different purposes and agriculture, forestry, and other land uses (AFOLU) as the main sources of greenhouse gases emissions. However, the amount of greenhouse gases emissions estimated from different sources varies among studies. Federici *et al*. (2015), for instance, reported a significant reduction in CO_2 emission from net forest conversion, which ranged from an average of 4.0×10^9 t CO_2 yr^{-1} during 2001–2010 to 2.9×10^9 t CO_2 yr^{-1} during 2011–2015. They also reported a net carbon sink globally, with an average net removal of -2.2×10^9 t CO_2 yr^{-1} for the period 2001-2010 and -2.1×10^9 t CO_2 yr^{-1} during 2011–2015. These results suggest that REDD+ projects can be promising interventions in the fight against climate change. Similarly, in its special report on climate change and land, summary for policy makers, IPCC (2018), also, reported that greenhouse gas emissions from AFOLU activities accounted for 23% (12.0 ± 3.0 Gt CO_2e yr^{-1}) of the total net anthropogenic emissions of GHGs globally during 2007-2016. These emissions represented 13% of CO_2, 44% of methane (CH_4), and 82% of nitrous oxide (N_2O). On the other hand, other sources (e.g., Tubiello *et al*., 2015; Zhu *et al*., 2016; Le Quere *et al*., 2018) claimed that about 30% of the total anthropogenic greenhouse gas emissions for the period 2008-2017 come from land use related activities. According to IEA (2015), carbon dioxide alone increased from its pre-industrial 280 ppm to the current 397 ppm. Other sources reported increase in concentration of carbon dioxide in the atmosphere from approximately 277 ppm in 1750 (the beginning of the industrial era) to 405.0±0.01 ppm in 2017 (Dlugokencky and Tans, 2018). These variations in estimates of greenhouse gases emissions emanated from differences in data sources and methodologies used for estimation, among others.

The increase in greenhouse gases in the atmosphere, notably carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), is causing global warming, which affects the global climate system as well as the environment (Pan *et al*., 2011; IPCC, 2018) by distorting the flux of solar radiation emitted by the sun (incoming) and the earth (outgoing) (Lal, 2010). The rise in global temperature due to radiative forcing of greenhouse gases has been estimated by different studies. For instance, IPCC (2007) estimated the increase in global temperature in the atmosphere at about 0.6 °C in the 1990s and 1.4 to 5.8 °C by 2100. In its recent special report, on the other hand, IPCC (2018) reported an increase in mean surface air temperature by 1.53 °C (very likely range from 1.38 to 1.68 °C) for the period 1850-1900 to 2006-2015. Similarly, in its special report on the impact of global warming of 1.5 °C, IPCC (2018) indicated that human activities are estimated to have caused approximately 1.0 °C of global warming above pre-industrial levels, with a likely range of 0.8 to 1.2 °C. It also projected that global warming is likely to reach 1.5 °C between 2030 and 2052 if it continues to increase at the current rate. These warmer temperatures, which may also alter precipitation patterns, have influenced agriculture and society through changing the start and end of growing seasons, reducing crop yields and freshwater availability at different scales, degrading biodiversity and forests (Kang *et al*., 2009; Amin *et al*., 2015; Chen *et al*., 2018; IPCC, 2018).

The climate change due to global warming affects societies through its negative impacts on land and food systems. Many reports indicated the impacts of climate change on crops', such as maize, soybean, rice, and wheat (Iizumi and Ramankutty, 2015 and 2016; Iizumi *et al*., 2017) and livestock (Fereja, 2016; Tigchelaar *et al*., 2018; Tiruneh and Tegene, 2018) production and productivity. Other studies (e.g., Ziska *et al,* 2016; Medek *et al*., 2017; Fanzo *et al*., 2018; Soares *et al*., 2019) documented the impact of climate change on nutritional quality of food. In line with this, studies have shown that increased carbon-dioxide levels lower the nutritional value of food staples like rice and wheat by decreasing their concentrations of protein, zinc, and iron. Similarly, other studies reported the potential impacts of climate change on water availability and security for different purposes (Urama and Ozor, 2010; Rochdane *et al*., 2012; Zhu and Ringler, 2012; Nkhonjera, 2017; Shrestha *et al*., 2017). These studies reported contrasting results for different localities under future climate; some regions will be wetter while others will be drier than today. Furthermore, the changes in temperature, particularly warming, are expected to create favorable conditions for new pests and diseases (Curtis *et al*., 2018; Ziska *et al*., 2018). The results of these different studies indicate the wide range of climate change impacts on different sectors, land, and society at large and the dire need to generate evidence for informing policy and developing viable adaptation and mitigation strategies.

Earlier studies also indicated that climate change, particularly change in temperature and rainfall, together with emissions of greenhouse gases have an effect on land suitability for crops (Tubiello *et al*., 2002; Jones and Thornton, 2003; Daccache *et al*., 2011). Fighting climate change and its negative impacts, therefore, remains the world's top most agendum. The Paris Agreement formulated the goal of limiting global warming during century well below 2 °C above the pre-industrial levels and called for rapid actions across the different sectors, such as agriculture, infrastructure, energy, and transport (Wynes and Nicholas 2017; Le Quere *et al*., 2018), while accommodating the growing human population (IPCC, 2018).

The two most common factors distorting the carbon cycle are land use change and combustion of fossil fuel (Lal, 2009). Studies have indicated that land use changes and land management could contribute to either greenhouse gas emission or sequestration (Smith *et al*., 2014; Tubiello *et al*., 2015; Le Quere *et al*., 2018). According to recent reports, around three quarters of the global ice-free land and significant proportion of the highly productive land area are being used for some purpose (Luyssaert *et al*., 2014; Erb *et al*., 2016; Venter *et al*., 2016). Furthermore, IPCC (2018) reported that one third of the used land has experienced some form of change in land cover. Recent studies by Tubiello *et al*. (2015) demonstrated that AFOLU activities could emit greenhouse gases through oxidation of organic materials and sink through fixation of organic matter via photosynthesis. The same study demonstrated that agricultural activities (crop and livestock production) emit mainly methane and nitrous oxide, while land use and land use change activities emit and remove or sink mainly carbon dioxide gas.

Assessing the carbon stock under different land uses is required for both scientific and climate related policy reasons. As explained by Tubiello *et al*. (2015), generating data on greenhouse gas emissions and/or sinks helps the scientific community to assess anthropogenic forcing of the atmosphere and suggest greenhouse gases', particularly carbon cycle, management scenarios. In terms of climate policy, accurate data on greenhouse gas inventories provides reliable evidence for supporting global actions under the United Nations Convention on Climate Change (UNFCCC). In the past, presence of reliable data has helped in implementation of different protocols, such as Kyoto Protocol's first commitment period, the adoption of the Bali Action Plan, and the Cancun Agreements. FAO (2011) has acknowledged the contribution of better quality AFOLU data for raising awareness on the urgent need to reducing emissions from deforestation and forest degradation (REDD+). Similarly, Stern (2007) demonstrated that early quantification of emission due to deforestation could be used to choose forestry as an effective, short-term climate change mitigation option.

Studies have estimated the likely changes in land suitability, potential yields, and agricultural production on the current suite of crops and cultivars available today (Schmidhuber and Tubiello, 2007; Daccache *et al*., 2011; Bonfante *et al*., 2015; Worqlul *et al*., 2019). Unwise use of land and its resources in one hand and the issue of sustainable agricultural production in the other are becoming a big concern at local and global scales (Gong *et al*., 2012; Singh, 2012). If efforts are not made to match land types with land uses in a rational way, sustainable production will be constrained, ecosystem will also be degraded and civilization may be collapsed. Hence, appropriate land use practices are required to address the ever-changing human demand. Climate models projected an increasing global mean surface temperature by 1.4 to 5.8 °C between 1990 and 2100, which is expected to be a much more rapid rate of warming than during the 20th

century (Cubash *et al.*, 2001; Majule, 2008). IPCC (2014) projected that global mean surface temperature change for the period 2016–2035 relative to 1986–2005 is similar for the four RCPs and will likely be in the range of 0.3 to 0.7 °C. However, the increase of global mean surface temperature by the end of the 21st century (2081–2100) relative to 1986–2005 is likely to be 0.3 to 1.7 °C under RCP2.6, 1.1 to 2.6 °C under RCP4.5, 1.4 to 3.1 °C under RCP6.0 and 2.6 to 4.8 °C under RCP8.5. Climate models projected not only an increase in mean temperature and a large variability of rainfall, but also forecasted more frequent heat waves and extreme droughts in the future (Fischer and Schär, 2010). The mean temperature during the growing season at the end of the 21st century will be higher than the most extreme seasonal temperature observed for the period 1900 to 2006 (Battisti and Naylor, 2009). In the future, these changes are likely to affect the suitability of a given parcel of land for crop production or any other use. Selecting land uses that are possible under these changed conditions might become imperative.

To this end, the Kyoto Protocol and following discussions point out a number of features that make carbon sequestration on forest and agricultural lands an attractive strategy for mitigating increases in atmospheric concentrations of greenhouse gasses. The rates at which GHGs are emitted and sequestered by different carbon pools determine the net emission in the atmosphere. Hence, types of land management practices determine the amount of carbon stored above and/or below ground, and play a significant role in decreasing the loss of carbon from the biosphere (Marland and Schlamadinger, 1997).

Ethiopia, a country where about 78% of the total population is rural and dependent on subsistent agriculture (FAOSTAT, 2018), is experiencing significant variations in spatial and temporal patterns of climate. Although there are limited comprehensive studies on climate change in Ethiopia, the National Meteorological Service Agency (2006) reported that the country experienced ten wet years and eleven dry years over the last 55 years analysed, demonstrating the strong inter-annual variability of rainfall. More recently, Negash *et al*. (2013) reported decreasing trends of the main and annual rainfall in northern, northwestern, and western parts of the country, with few grid points in eastern parts of the country experiencing an increasing annual rainfall. This inter-annual variability of climate has impact on biomass production and energy transfer at ecosystem level, which in turn affects the carbon sequestration potential of carbon pools. Hence, the livelihoods of smallholder farmers, who have low technical and financial capacity to adapt to and cope-up with such climate variabilities, will be at risk. Furthermore, the low productivity of the system aggravates land use/land cover changes in search of fertile and productive land, which mostly occurs at the expense of forest and grazing lands.

Similarly, the rural population in Hades Sub-watershed are primarily practicing agriculture as their main economic activity. Triggered by population growth and decline in fertility of the majority of land that has been under cultivation for the last many years, agriculture is expanding dramatically into forest and marginal areas in the study sub-watershed. The consequences of this expansion are aggravating environmental degradation, food insecurity in the area, and vulnerability of the people to climate change and variability impacts (DWARDO, Personal communication, 2015).

1.2. Statement of the Problem

Population growth, climate change and heavy reliance on subsistent agriculture has led to decline in soil and land productivity, which eventually causes land degradation (McKenzie and Williams, 2015; Keesstra *et al*., 2016; Davis *et al*., 2017; Cowie *et al*., 2018). Similarly, in Ethiopia agricultural production is constrained by rainfall variability and land degradation (Abegaz *et al*, 2016; Mekuriaw, 2017). Land degradation manifested in the form of soil erosion is one of the major biophysical constraints in the country (Yihenew and Getachew, 2013). Land degradation forced to land use/ land cover change, which has contributed to massive anthropogenic emissions of carbon dioxide (Gómez *et al*, 2006). Similar to most other areas in rural Ethiopia, rural population in Hades sub-watershed are relying heavily on subsistence agriculture for making their living. Consequently, agriculture has been expanding radically into forest and grazing lands in search of piece of land and fertile soils (Muktar *et al*., 2019). Because of this expansion, significant proportion of land under vegetation cover is now converted into agricultural land. In spite of this expansion, the sector remains less productive and constrained by various natural and anthropogenic mishaps, exposing majority of the community members to food insecurity (Doba Woreda Agricultural and Rural Development Office, 2015). The type of agriculture the farmers of the study area have been practicing might not allow sequestration of carbon in the soil since nothing is left or returned to the soil as organic input. Furthermore, there is massive deforestation for different purposes (Kidanemariam *et al*., 2015). Obviously, such activities are continuously depleting the carbon stock in different carbon pools and increasing emission into the atmosphere. Furthermore, whether the current land uses in the study area are being practiced according to the suitability of a given parcel of land or not has not been assessed scientifically. Likewise, the response of some of the major crops grown in the study area to future climate has not been investigated.

Therefore, changing the way land has been and is being used in the study area could improve the productivity of land, carbon sequestration, carbon stock, and reduce greenhouse gas emissions. This stipulates for selecting best land use types based on suitability evaluation of the land units for a given use. Furthermore, despite the global interest of carbon stock and sequestration assessment (UNFCCC, 2014), little attempts have been made to estimate the carbon stock under different land uses. Thus, understanding the current and future carbon stock at watershed level and identifying alternative land use scenarios is vital in the study area in particular and in Ethiopia in general for enhancing productivity and reducing GHG emissions.

1.3. Rationale of the Study

Massive land use/land cover change that has resulted and is resulting in degradation of forest and soil resources is occurring in the study area (Muktar *et al*., 2019). Thus, the current land management practices may not be allowing sequestration of carbon in carbon pools; rather they are depleting the carbon stock, increasing emission of CO_2 into the atmosphere, and thereby aggravating climate change (Kidanemariam *et al*., 2015). This has led to reduction in food production, forcing communities to rely on external food aid for their survival. Given the importance of improving carbon stock in mitigating climate change and enhancing productivity of soil, it is necessary to understand the potential of different carbon pools in storing carbon at a watershed level. Moreover, countries are obliged to estimate and report their GHG emission to the United Nations Framework Convention on Climate Change (UNFCCC, 2014). Despite a growing effort to understand the impacts of climate change in the country (Fikru *et al*., 2018; Haileab, 2018; Meron *et al*, 2018), very limited comprehensive works have been done on carbon stock and sequestration assessment of major land uses and carbon pools at watershed level in the country (Amanuel *et al*., 2018; Senait *et al*., 2019; Yared *et al*., 2019). Furthermore, no research has been done in the study area to develop alternative land uses that ensure increased biomass production and sustainable use of the natural resource-base under likely changing climatic conditions in the coming 50 years.

Although land suitability evaluation is believed to provide basic information for making rational land use decisions, there has not been such effort in the study area. Because of this gap, most of the land in the study area has been put for a use that it is not suitable for. This has resulted in environmental degradation and decline in ecosystem services. Furthermore, how major crops grown in the study area may respond to changing climate in terms of biomass yield and, hence, organic carbon sequestration is not understood. This lack of adequate information may hamper the development of land use alternatives that enable mitigate the effects of climate change through sequestering carbon in soil and vegetation, reducing CO_2 emission, and increasing agricultural productivity. Thus, understanding the potential and constraints of the sub-watershed in relation to GHGs emission and sequestration is vital to set clear recommendations on the maintenance and enhancement of carbon stock and sequestration in the years to come where climate change is expected. Therefore, conducting a study that generates information on carbon stock status, identifies alternative land use types (land suitability evaluation) that enhance the carbon stock and reduce GHG released into the atmosphere, and evaluates biomass yield of selected cereal crops under changing climate was felt necessary.

1.4. The Research Goal

The goal of the study is to enhance production and productivity, and reduce greenhouse gas emission at Hades Sub-watershed through use of land units according to their suitability under current and changing climate. The research addressed the following important research questions:

- Do land use/cover types affect carbon stock in the study area?
- Is the land in the study area suitable for the current major land utilization types being practiced?
- If the current land uses are to be continued with the existing management practices, what will happen to the carbon stock status and sequestration potential in the future?
- Will climate of the study area change in the coming 50 years?
- What will happen to carbon stock status and sequestration under changing land uses and climate over the coming 50 years?

- Can AquaCrop model project biomass yield and organic carbon content of late-maturing sorghum and maize varieties with reasonable accuracy?

The research, therefore, tried to look for answers to the above-stated and other related research questions. The general objective of the study was to evaluate current carbon stock under different land use/cover types, undertake physical land suitability evaluation for rainfed production of selected crops, and estimate carbon sequestration of selected land utilization types under changing climatic conditions at Hades Sub-watershed. The specific objectives were to:

1. evaluate the status of carbon stock under major current land use/land cover types,
2. undertake physical land suitability evaluation of the current major land utilization types and identify alternative land uses that reduce greenhouse gas emissions in the future, and
3. project biomass and corresponding organic carbon yield potential of selected land uses under projected climate over the coming 50 years.

1.5. Outline of the Study

This thesis is structured to have different components dealing with different aspects of the research. A general abstract is presented in the preliminaries section of the thesis. The general abstract gives brief but informative highlight about the key findings of the research. Chapter one of the thesis contains brief background of the study, statement of the problem, rationale of the study, and the goals of the study. Chapter 2 is literature review. This chapter presents literature review on major topics of the research, which include carbon stock, land suitability evaluation, and projection of climate, biomass, and organic carbon yield. Chapter 3 is the material and method part. This chapter describes the methodologies followed and materials used while executing the three experiments of the research. Chapter 4 presents results of the three experiments: organic carbon stock assessment, physical land suitability evaluation for rainfed production of major crops, and projection of carbon sequestration potential of selected land utilization types under projected climate. Chapter 5 contains the detailed discussions on the research findings of the three experiments. Conclusions and Recommendations are presented in Chapter 6. The thesis also contains ‘References’ chapter whereby all the sources cited in the main body of the thesis are duly acknowledged. At the end of the thesis, tables and figures that are not included in the main body of the thesis are included as Appendix Tables or Figures for further reference. The next chapter, Literature Review, presents relevant and up-to-date review on most important topics of this thesis research.

CHAPTER TWO

LITERATURE REVIEW

In this chapter, a brief literature review on relevant topics of the research is presented. The topics for the review were selected based on their relevance to the discussion of the research findings in this study. The review on carbon stock includes basic concepts of the carbon cycle and major carbon pools with extensive review on carbon stock status of different land uses as well as brief review on carbon trading. Similarly, the need for land suitability evaluation, general concepts of land suitability evaluation, characterization of land resources in land suitability evaluation, definition of major terminologies used in land suitability evaluation, and methods of land suitability evaluation are the major literature review topics for the work on physical land suitability evaluation. For the third research topic, review was made on biomass production of agricultural crops under changing climate (focusing mainly on impacts of temperature and precipitation), carbon sequestration in agriculture, representative concentration pathways for projecting climate, and modeling crop biomass production. Under each experiment, an introduction is also included.

2.1. Carbon Stock

2.1.1. Introduction

The prominent factor deriving climate change is the increase in the concentration of greenhouse gases (GHGs) in the atmosphere. The ever increasing concentrations of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and other GHGs have distorted the balance between the incoming and the outgoing solar radiation emitted by the Sun and Earth, respectively (Lal, 2010; Ciais *et al*., 2013). IPCC (2007) estimated the increase in global temperature because of radiative forcing of GHGs in the atmosphere at 0.6 °C in the 1990s, while highlighting that this is expected to increase by 1.4 to 5.8°C by 2100. According to IEA (2015), carbon dioxide has increased from its pre-industrial 280 ppm to 397 ppm (IEA, 2015). On the other hand, Dlugokencky and Tans (2018) reported a 128 ppm increase in concentration of carbon dioxide in the atmosphere between 1750 (beginning of pre-industrial period) and 2017.

The two most common factors distorting the carbon cycle are land use change and combustion of fossil fuel (Lal, 2009; Ciais *et al*., 2013). Practically, about 75% of the global CO_2 emissions come from the combustion of fossil fuels in transportation, building heating and cooling, and manufacture of cement and other goods (Steen, 2000**)**. The Agriculture, Forestry, and Other Land Use (AFOLU) sector is responsible for just under a quarter of anthropogenic GHG emissions mainly from deforestation and agricultural emissions from livestock, soil, and nutrient management (Smith *et al*., 2014). In Ethiopia, the emission from fossil fuel generated 2.3 million tonnes of CO_2 in 1990 and the figure increased to 8.5 million tonnes of CO_2 in 2013 (IEA, 2015). Land use change, especially conversion of a natural system into a managed system, results in alteration of the carbon balance (Yihenew and Getachew, 2013). There is also tremendous evidence showing the negative impact of agriculture on carbon stock (Lemenih *et al*., 2005; Yeshanew *et al*., 2007; Girmay *et al*., 2008). However, agriculture is among the land use practices that emit as well as sequester CO_2. It may lose soil organic matter due to intense decomposition following soil plowing, removal of aboveground biomass during harvest, and severe soil erosion inherent in these activities (Zhongkui *et al*., 2010). Nevertheless, if proper land use and management practices are put in place, agriculture can serve as an important sink (Wright and Hons, 2005; Lal, 2006; Pan *et al*., 2009; Lipper *et al*., 2011).

In the tropics, deforestation is the second most important source of greenhouse gases after fossil fuel combustion (Don *et al*., 2011). Conversion of forestland to other land uses, such as agriculture, enhances decomposition and removal of carbon through harvest (Lasco, 2002; Janzen, 2004; Lemenih *et al*. 2005; Girmay *et al*., 2008; IPCC, 2013). On the contrary, a significant increase (50%) of soil carbon was reported after conversion of arable land in to forestland (Dawson and Smith, 2007; Yang *et al*, 2018).

The positive effects of other land uses, such as agroforestry, on carbon balance were also highlighted. In soils that were previously under cultivation, agroforestry systems were found to be highly effective in restoring soil carbon (Wang *et al*., 2015). In line with this, higher aboveground carbon in coffee agroforestry (61.5±25.0 t ha^{-1}) than in woodland, pasture, and cropland, but slightly less than that in natural forest (82.0±32.1 t ha^{-1}) was reported in southwestern Ethiopia (Dereje *et al*., 2016). The same study further indicated that about 59.5 t ha^{-1} organic carbon could have been lost if the coffee agroforestry had been converted into cropland.

Similar to the other land uses, rangelands and grazing areas are storing carbon above and below ground. In Europe, an increase in carbon stock following conversion of cropland into grassland was reported (Freibauer *et al*., 2004). Though there is scanty information on carbon stock of grazing lands in highland areas of Ethiopia, 128.39 t ha^{-1} belowground (soil and root) and 13.11 t ha^{-1} aboveground organic carbon was reported in the communally managed semi-arid rangelands in southern Ethiopia (Bikila *et al*., 2016).

Hence, understanding the relationship between land-use systems and carbon stock is essential since every land use system has either positive or negative impact on the carbon balance. Besides, considering the potential and constraints of a watershed in relation to carbon stock is vital to set recommendation on the maintenance and enhancement of carbon stock. In Ethiopia, few area-specific researches have been conducted on organic carbon stock and sequestration (Girmay *et al*., 2008; Adugna *et al.* 2013; Tura *et al*, 2013; Hamere *et al*, 2015; Muluken *et al*, 2015; Tibebu and Teshome, 2015; Dereje *et al.*, 2016). The available researches are limited in their scope, mostly concentrating on soil carbon and giving much less emphasis to the carbon stock of the various carbon pools at watershed level. Furthermore, the impact on carbon stock of smallholder subsistence farming, mostly characterized by low level of management where limited or no inputs are used, under high population pressure has not been studied comprehensively. Under the looming climate change, such information on carbon emission and sequestration is essential for developing strategies that enhance productivity (through increasing carbon stock) and abate greenhouse gas emissions (through enhancing carbon sequestration). In view of this backdrop, this study assessed the current carbon stock under different land use types and carbon pools in Hades Sub-watershed, eastern Ethiopia.

2.1.2. Basic cconcept of carbon cycle

The carbon cycle is the Earth's most fundamental biogeochemical cycle, yet much of it remains unknowable; it is a reflection of a planet with life, and its relevance to life has long been apparent (Sellers *et al*, 2018). The carbon cycle binds together the Earth's ecosystems and their inhabitants. The main pools of actively cycling carbon are atmosphere (7.85×10^{11} tonne (t) C), biota (4×10^{11}–6×10^{11} t C), soil organic matter (1.5×10^{12} –2×10^{12} t C), and the ocean (39×10^{12} t C) (Smil, 2002). All of these C pools are connected. Agriculture, Forestry and Other Land Use (AFOLU) activities accounted for around 13% of CO_2 emission during 2007-2016 (IPCC, 2018). Anthropogenic CO_2 emissions to the atmosphere were 555 ± 85 x 10^6 t C between 1750 and 2011. Of this amount, the largest (375 ± 30 x 10^6 t C) was from fossil fuel combustion and cement production, and the remaining was due to land use/ land cover change. Studies indicated that out of this amount about half of the emission (240 ± 10 x 10^6 t C) remained in the atmosphere, while the remaining was removed by sinks and stored in carbon pools (Ciais *et al*., 2013).

Atmospheric CO_2 enters terrestrial biomass via photosynthesis at a rate of about 1.2x10^{11} t C per year (gross primary productivity). Nevertheless, about half of that is soon released as CO_2 by plant respiration, leaving a net primary production (NPP) of about 6x10^{10} t C per year. This amount is stored at least temporarily in vegetative tissue, but most eventually enters soil upon senescence. At the same time, heterotrophic respiration (largely by soil microorganisms) and fire return an amount roughly equivalent to NPP back to atmospheric CO_2, closing the loop (Janzen, 2004).

In terrestrial ecosystems, the source of soil organic carbon input is from photosynthesis or net primary productivity. Assimilates can be transferred directly to the roots via the phloem or can be converted to biomass that might be transferred to the soil via litter. The ‘assimilate-fed’ and the ‘litter-fed’ pathways have also been named ‘autotrophic’ (respiration of the roots *sensu stricto* and their mycorrhizal symbionts and the microbiota of the rhizosphere) and ‘heterotrophic’ components of soil respiration (Kusch *et al*., 2010).

2.1.3. Major carbon pools

2.1.3.1. Soil carbon pool and its status under different land uses

Status of soil organic carbon in soils

The global soil organic carbon (SOC) stock of ~ 1.5 × 10^9 t is two and three folds higher than that of the atmosphere and vegetation, respectively (Lal, 2016). The current estimate for global SOC stock is 1,400 ± 150 x 10^9 t C to 1 m depth and 2,060 ± 220 x 10^9 t C to 2 m depth (Köchy *et al*., 2015; Batjes, 2016). Similarly, Sanderman *et al*. (2017) reported that SOC across the globe for the year 2010 were 863 x 10^9, 1,824 x 10^9, and 3,012 x 10^9 t C in the upper 0.3, 1, and 2 m of soil depth, respectively. In line with this, many studies reported that soil organic carbon content deceases with increase in soil depth (Grüneberg *et al*., 2010; Sharma *et al*., 2014; Zádorová *et al*., 2015; Ehrenbergerová *et al*., 2016; Ali *et al.,* 2017; Henok *et al*., 2017; Ghimire *et al*., 2018; Yared *et al*, 2019). However, very few studies (e.g., Rumpel and Kögel-Knabner, 2011; Twongyirwe *et al*., 2013) recorded increase in SOC with soil depth and attributed this to plant roots and root exudates dissolved organic matter, bioturbation, translocation of particulate organic matter to the deeper layers, and transport of clay-bound organic matter in certain soil types.

In addition to soil depth, studies revealed that, under given management conditions, SOC can be affected by soil texture through its capacity to stabilize soil organic matter due to interactions between SOM, mineral surface area, and electrostatic binding sites (Sollins *et al*., 1996; Baldock and Skjemstad, 2000). In agreement with this, Dlamini *et al*. (2014) claims that fine-textured soils have more C input owing to their capacity to store more plant-available water, retain more nutrients, and provide better soil structure for plant growth. Contrary to this, Chan *et al*. (2010) believes that coarse-textured soils are expected to have low C input due to a faster rate of decomposition since these soils lack the protection generally afforded by an abundance of clay particles. Yet, O'Brien *et al*. (2015) argues that texture has not always been observed to affect SOC at a landscape scale. Ehrenbergerová *et al*. (2016) adds biological activity, microbial community composition, the molecular recalcitrance of organic matter, soil mineralogy, structure, continuous temperature, and humidity to the list of factors that influence carbon sequestration potential and carbon turnover.

From the foregoing discussions, it is evident that soils play a key role in global carbon budget and greenhouse gas effect. This affects the atmospheric carbon pool since many processes that influence the SOC take place at the land-atmosphere interface (Tebkew, 2018). There is continuous exchange of carbon between soils and the atmosphere through accumulation and decomposition, and release of carbon dioxide (CO_2) and methane (CH_4) (Schrumpf *et al*., 2008). Consequently, any net carbon loss from soils will increase the CO_2 concentration in the atmosphere and water bodies, whereas net accumulation in soil carbon can contribute to the reduction of the atmospheric carbon pool (Lal, 2004). Sustaining soil organic matter (SOM) is of paramount importance with respect to availability of plant nutrients and improvement of the soil's physical, chemical, and biological properties (Kundu *et al*., 2006; Lefèvre *et al*., 2017), all of which have positive contributions in SOC sequestration.

Soil organic carbon and land use

Studies have indicated that land use type is the main factor governing SOC content by altering soil properties and supply of soil nutrients (Li *et al*., 2012; Yan *et al*., 2012; Yared *et al*., 2019). In connection with this, large number of studies reported that conversion from natural ecosystems into managed systems will lead to significant loss of SOC (IPCC, 2013; Poeplau and Don, 2013; Yihenew and Getachew, 2013; Ciais *et al*., 2013; Guillaume *et al*., 2015; Fan *et al*., 2016; Iqbal and Tiwari, 2016). Empirical studies reported loss of soil C that ranges from 2.3 to 8.0 t ha^{-1} per year following conversion of land uses (Assefa *et al*., 2017; Kassa *et al*., 2017). Similarly, Belay and Getaneh (2018) predicted 40% loss of soil organic carbon after 40 to 50 years of converting forests into agricultural land. A model-based study conducted in Birr watershed in Ethiopia projected a net loss of 20.7 t SOC ha^{-1} within 100 years if natural forest is converted to cropland (Tebkew, 2018). Contrary to this, improvement in SOC storage due to shifting from systems without trees to agroforestry systems was reported by several studies (Priano *et al.* 2018; Stefano and Jacobson, 2018).

Land use changes have several undesirable consequences like decline in soil fertility, soil carbon and nitrogen stocks (Tesfaye *et al*., 2016; Henok *et al*., 2017). Conversion of forestland to other land uses, such as agriculture, enhances decomposition due to tillage and removal of carbon through harvest (Girmay *et al*., 2008; IPCC, 2013). Noponen *et al*. (2013) indicated that areas covered with vegetation have high SOC than open areas. However, the potential contribution of building SOM in increasing crop production and minimizing the environmental impact of agriculture has not yet been broadly quantified (Chabbi *et al*., 2017; Hatfield *et al*., 2017). Generally, equilibrium between the rate of decomposition and rate of supply of organic matter is disturbed when forests are cleared and land use and land cover is changed (Lal, 2004). This is primarily because in terrestrial ecosystems the source of soil organic carbon input is from photosynthesis or net primary productivity.

Soil organic carbon status in forests

Carbon input to forest soils comes mainly from the litter layer on the soil surface by leaching and from root exudates of trees including fungal products from their associated mycosphere (Heng *et al*., 2016). Some recently conducted studies in Ethiopia reported different levels of soil organic carbon under different forestlands. Tulu *et al*. (2011) for Church forest, Aduga *et al*. (2013) for Egu forest, Mohammed *et al*. (2014) for Tara Gedam forest, Hamere (2015) for Gedeo forest, Muluken (2015) for Adaba Dodola community forest, Tibebu and Teshome (2015) for Simen Mountain National Park forest, and Abyot *et al*. (2019) for Gerba-Dima moist Afromontane forest reported SOC stock values that ranged from 135.94 to 277.56 t C ha^{-1}. According to these studies, the SOC stock under the forest varied from 29 - 47% of the total carbon stock. Moreover, a study made in Gacheb catchment of White Nile Basin indicated presence of high soil organic carbon stock in forest and agroforestry lands as compared to croplands (Henok *et al*., 2017). Similarly, Ali *et al.* (2017) reported higher SOC stock in forestland compared to arable land and pastureland.

Soil organic carbon status in agro-forestry systems

Agroforestry systems are believed to have a higher potential to sequester C than pastures or field crops (Sharrow and Ismail, 2004; Kirbyand Potvin, 2007; Nair 2011; Stefano and Jacobson, 2018). Because of the presence of woody perennials and diversity in species composition, agroforestry has immense contribution in protecting soil from erosion and enhancing SOC through addition of soil organic matter as well as creating modified microclimate that retards OM decomposition (Henok *et al*., 2017). According to the World Agroforestry Centre, ICRAF, 43% of the planet's agricultural lands have more than 10% tree cover (Zomer *et al*., 2009). Noponen *et al*. (2013) indicated that, where agroforestry systems are established on soils more depleted in SOC concentration, they provide a greater potential for climate change mitigation through higher SOC. Trees in agroforestry systems, by controlling soil erosion and facilitating nutrient cycling, can improve the soil physical and chemical properties (Manjur *et al.,* 2014; Desalegn and Zebene, 2017; Salve *et al*., 2018). This improvement in soil properties can, in turn, support good plant growth and, thus, biomass production for organic carbon maintenance. In consent with this, Stefano and Jacobson (2018) confirmed that shifting from systems without trees to agroforestry systems resulted in an improved SOC stock. The findings of these studies clearly demonstrate the key role agroforestry systems could play in carbon sequestration and climate change mitigation in a given agricultural system. Cognizant of this, agroforestry system was considered in the Keyoto Protocol as one of the GHG mitigation strategies.

Studies conducted in Mexico and Indonesia revealed that the carbon stock in coffee agroforestry was higher than that in sun coffee, maize, and other traditional systems (Noordwijk *et al.*, 2002; Soto-Pinto *et al*., 2010). A study conducted in Guatemala by Schmitt-Harsh *et al*. (2012) reported that about 30% of the total carbon stock (74 to 243 t ha $^{-1}$) in coffee agroforestry was stored in the soil. Likewise, Ha¨ger (2012) found that the highest carbon stock of coffee agroforestry, which had a total carbon stock of 82 to 198 t ha $^{-1}$, in Costa Rica was recorded in the soil. Ehrenbergerova´ *et al*. (2016) stressed that variation in carbon stock in agroforestry systems depends on the type of shade trees used. Accordingly, the study reported 119.9 ± 19.5, 177.5 ± 14.1, and 162.3 ± 18.2 t ha $^{-1}$ total carbon stock when Inga, Pinus, and Eucalyptus trees, respectively, were used as shade trees. Of this total carbon, 69, 57, and 59% was stored in the soil for the respective shade trees.

In Ethiopia, the SOC stock for the 0 - 60 cm layer of agroforestry systems ranged between 109 and 253 t ha $^{-1}$, with the 0 - 30 cm layer accounting for between 50 and 83% (Mesele *et al*., 2013). However, growth-rate differences among tree species and the “native vs. exotic” species controversy are among the widely debated but not yet resolved biological issues related to C sequestration by trees in agroforestry systems (Nair *et al*., 2009).

Soil organic carbon status in grazing lands

Grasslands, which make about 40% of the earth’s land mass, cover about 10% of terrestrial biomass (Conant, 2001; Wang and Fang, 2009). According to global estimates, as much as 30% of terrestrial SOC resides in grassland soils (Schuman *et al*., 2002; Derner and Schuman, 2007). This makes grasslands one of the most important pools of SOC with immense potential for carbon sequestration (Conant *et al*., 2001). Grazing, however, affects the contribution of grasslands to SOC by distorting biomass production, supply into the soil, and altering decomposition of organic matter (Pineiro *et al*., 2010). Grassland productivity, including nutrient supply into the soil, is influenced by management practices, edaphic and climate related factors (Blair *et al*., 1995). A research conducted in the Republic of South Africa revealed that reduction of grass cover from 100 to 5% increased SOC losses by 213% due to erosion processes in particulate forms (Dlamini *et al*., 2014). Several studies have indicated presence of high soil organic carbon stock in grazing lands as compared to croplands and attributed this to the presence of high grassroots biomass turnover and absence of tillage (Yoseph *et al.*, 2017; Yared *et al*., 2019). Enhancing carbon stock in grazing lands can be achieved through improved grazing management such as optimizing stock number, rotational grazing, and fertilization (Guo and Gifford, 2002).

Soil organic carbon in croplands

Soil organic carbon across the globe in lands classified as cropland contained an average of 62, 127, and 198 t C ha $^{-1}$ in the upper 0.3, 1, and 2 m of soil depth (Fried *et al*., 2010). In cropping systems, the amount of SOC is a function of the rate of SOM decomposition and the quantity and composition of crop residue returned into the system. Besides, crop residue management, soil properties, and climatic factors have impact on the rate of decomposition and microbial activity. It is known that the amount of SOC in a given cropping system will depend on the amount and quality of crop residue applied (Rasmuseen *et al*., 1980), and the size and extent of the reservoir (Hassink and Whitemore, 1997). Biomass burning or decomposition and release of SOC following cultivation are among the causes of C emission in croplands (Korschens, 1998). Yeshanew *et al*. (2007) reported substantial loss of organic C and Nafter 26 years of cultivation in Ethiopia. The study claims that break-up of soil aggregates and increased aeration caused by tillage are the prime reasons for the high rate of organic matter decomposition observed in croplands. Similar studies confirmed that lack of biomass addition to the top soil, crop residue removal, and conventional tillage practices in agricultural production systems enhance carbon losses from the soil (Yang *et al*., 2004; Baker *et al*., 2007; Smith, 2007).

Yet, agriculture can be a part of the solution of C sequestration if properly managed. Carbon sequestration can be enhanced through different options, such as judicious land-use, improved soil and plant management technologies, conservation tillage, and restoration of degraded soils (Lal *et al*., 1997). Alan and Frank (2005) reported that increased cropping intensity coupled with none tillage enhanced residue production and led to higher SOM levels, which is also likely to increase nutrient cycling. Lal (2006) mentions judicious use of fertilizers, irrigation, and other amendments as promising examples of measures to enhance the carbon stock in agricultural lands.

2.1.3.2. Vegetation and vegetation-related carbon pools

Aboveground vegetation carbon pool

Forests, particularly primary forests, play an important role in global carbon (C) cycle because they store large quantities of C in vegetation (live and dead), soil, and microorganisms, and exchange C with the atmosphere through photosynthesis and respiration. FAO and ITPS (2015) estimated the carbon in plants at 638 x 10^9 t and claim that this pool represents about 44% of that in the terrestrial systems. This estimate testifies forests' decisive role in mitigating climate change by either reducing net C stock losses or increasing long-term average C stocks and their associated economic benefits (FAO, 2005; Zhou *et al.*, 2006; Sheikh *et al.*, 2009; IPCC, 2009). However, evidences collected from 1991–2015 indicated that, globally, forestland was a net source of CO_2 emission, averaging 1.52 x 10^9 t CO_2 yr^{1}. These corresponded to emissions from deforestation of 4.04 x 10^9 t CO_2 yr^{1} counterbalanced by net removals in forest of -2.52 x 10^9 t CO_2 yr^{1} (Federici *et al.*, 2015). IPCC (2007), on the other hand, indicated that deforestation in forest singly contributes emission of about 5.9 x 10^9 t of CO_2 annually in the world and halting of it can reduce about 17.4% atmospheric CO_2.

African forests are among the most pristine on the Earth and contain large carbon stocks in biomass, reaching up to 255 t C ha^{-1} in tropical areas (Palme, 1999). However, FAO (2010) reported reduction in forest biomass in this region primarily due to conversion of forestlands to other land uses. Deforestation and inappropriate land-use practices are among the causes of global warming through reduction of carbon sequestration potential of a given system and increasing emission of CO_2 into the atmosphere (Paustian *et al.*, 2000; van der Werf *et al.*, 2009; IPCC, 2013; Cui *et al.*, 2015). The case is also true for Ethiopia where its forest coverage has reduced from about 35% at the turn of the century to 2.4% in 1992 (EPA, 1998). The forest resource of Ethiopia has stored 2.76 x 10^6 t of carbon in the aboveground biomass (Yitebitu *et al.*, 2010).

Different sources made estimates of the carbon stock in African forests. Accordingly, IPCC (2006) for tropical dry forests, Gibbs and Brown (2007) for all forms of forests in sub-Sahara Africa, and IPCC (2010) for eastern and southern Africa forests estimated 73, 143, and 58.9 t C ha $^{-1}$, respectively. In Montane forests of central Mexico, Ordo´n˜ez *et al*. (2008) reported total aboveground carbon stock of 162.9 t C ha $^{-1}$ for degraded forest and 267 t C ha $^{-1}$ for native forest.

In Ethiopia too, a number of recent studies have reported the contribution of forests to carbon stock. Some of the studied forests include selected church forests (Tulu *et al*., 2011), Egdu forest (Adugna *et al*., 2013), Tara Gedam forest (Mohammed *et al*., 2014), Adaba Dodola community forest (Muluken *et al*., 2015), Simen mountain national park forest (Tibebu and Teshome, 2015), and Gerba Dima moist Afromontane forest (Abyot *et al*., 2019). These studies focused on aboveground carbon stock and reported values that ranged from 122.85 t C ha $^{-1}$ (selected church forests) to 306.37 t C ha $^{-1}$ (Tara Gedam forest). Adugna *et al*. (2013) and Hamere *et al*. (2015) explained that the high aboveground carbon stock is due to the presence of high-density trees with larger diameter at breast height (dbh). Most of the carbon stock values reported by these studies are higher than those reported for other regions in Africa. This could be due to variation in climate, species composition, management, allometric equations used, and scale of the assessment.

Besides the natural forest, agroforestry has also potential to sequester carbon above and below ground. It is well understood that agroforestry is a sustainable land management system that has both productive and service functions. One of its service functions is CO_2 mitigation through an increase in carbon sequestration (Schroth *et al*., 2002). Agroforestry provides construction material and fuel wood (Rice and Ward, 2008), which otherwise will be obtained from forests. It also reduces expansion of subsistent agriculture (Noponen *et al.*, 2013) by increasing agricultural production from a unit of land.

Coffee agroforestry is among the various agroforestry systems in the globe. Quantification and understanding of the carbon stock of shade grown coffee systems is important for the development of sound climate change mitigation strategies (Schmitt-harsh *et al*., 2012). A study in Villa Rica district (Peru) has shown that total aboveground biomass varied with the type of shade trees used as well as between coffee under shade and sun coffee sites. Ehrenbergerová *et* *al*. (2016) reported higher aboveground biomass carbon stock for coffee under legume shade trees than coffee under Pinus and Eucalyptus species, and sun coffee. In Ethiopia, Mesele *et al*. (2013) reported that total aboveground biomass (trees, coffee, enset, herbs, and litter) C stock in agroforestry ranged from 16 to 93 t C ha^{-1} of which trees accounted for the largest proportion.

In Costa Rica, Ha¨ger (2012), depending on the types of shade trees used, recorded 13.9 to 23.2 t C ha^{-1} for shade trees in an organic agroforestry coffee plantations. Similarly, Ehrenbergerová *et al*. (2016) reported a biomass carbon stock of shade trees that ranged from 27.5 ± 3.2 to 57.5 ± 4.5 t C ha^{-1} in Peru. A study conducted in Guatemala by Schmitt-Harsh *et al*. (2012) revealed that, on average, 47% of the total carbon stock in agroforestry plots was stored in the biomass of shade trees. Furthermore, studies demonstrated that number of plants per hectare (density of plants) is another important factor that affects carbon stock in agroforestry systems. Accordingly, lower carbon stock value was obtained for higher plant density (Ha¨ger, 2012) and higher carbon stock for lower plant density due to size difference of shade trees (Hergoulac´h *et al*., 2012). However, there are ample evidences that show the carbon stock in forests is greater than that in agroforestry systems (Noordwijk *et al*., 2002; Schmitt-Harsh *et al*., 2012).

Root carbon pool

Roots make a significant contribution to SOC (Strand *et al*., 2008). About 50% of the carbon fixed in photosynthesis is transported belowground and partitioned between root growth and assimilation to soil organic matter (Nguyen, 2003). Hence, roots help in accumulation of SOC by their decomposition. Besides, roots supply carbon to soil through a process known as rhizodeposition (Weintraub *et al*., 2007).

Depending on rooting depth, a considerable amount of carbon is stored below the plow layer and better protected from disturbances, which leads to longer residence times in the soil. With some trees having rooting depths of greater than 60 m, root carbon inputs can be substantial, although the amount declines sharply with soil depth (Cairns *et al*., 1997; Hirte *et al*., 2017). Tree based systems have a greater potential to sequester C into more stable stocks in deeper soil than some treeless systems (Haile *et al*., 2010); this is strongly influenced by other site- and land use change-specific variables (Noponen *et al*., 2013).

A study in central highlands of Mexico indicated that the root carbon stock of agricultural lands, grasslands and degraded forest were 0.20 ± 0.10, 0.02 ± 0.02, 13.10 ± 1.30 t C ha^{-1}, respectively (Ordonez *et al*., 2008). Similarly, Ullah and Amin (2012) found 14.61 t C ha^{-1} underground carbon in the natural hill forests of Bangladesh. In semi-arid pastoral areas of Kenya, Dabassso *et al*. (2014) reported below ground biomass carbon of 0.93± 0.16, 1.3 ± 0.16 and 0.44 ± 0.16 t C ha^{-1} in woodlands, shrub lands and grasslands, respectively. In Ethiopia, Mesele *et al*. (2013) obtained 5.7 ± 3.0 t C ha^{-1} root carbon under coffee agroforestry. A study made in Gerba Dima moist Afromontane forest in south western Ethiopia found 45.97 ± 3.46 t C ha^{-1} (Abyot *et al*., 2019).

Litter carbon pool

Litter contributes to carbon stock through breakdown of dead plant organic materials into particles of progressively smaller size (Kutsch *et al*., 2010). Aboveground litter decomposition is one of the factors that influence the mechanism of species driven carbon sequestration in soil (Lemma *et al.*, 2007). The quality of litter such as lignin content and plant species diversity in a given system are important in terms of controlling rate of litter decomposition and supply of carbon into the soil (Mafongoya *et al*., 1998; Lemma *et al*., 2007).

According to Brown and Lugo (1982) and Brown (1997), the mean carbon stock value of litter in tropical dry forests varies between 2.6 - 3.8 and 2 - 16 t C ha^{-1}, respectively. Ordo´n˜ez *et al*. (2008) reported litter carbon stock of 2.6 t C ha^{-1} for degraded forests and 4.1 t C ha^{-1} for native forests of Central Mexico. Recent studies conducted in Ethiopia revealed the presence of wide variations in terms of litter carbon stock under different forests. The values ranged from a minimum of 0.026 t C ha^{-1} for Gerba Dima moist Afromontane forest (Abyot *et al*., 2019) to a maximum of 4.95 t C ha^{-1} for Church forest (Tulu *et al*, 2011). Other studies (e.g., Adugna *et al*., 2013; Mohammed *et al*., 2014; Muluken *et al*., 2015) reported intermediate values.

In addition to forests, the contribution of agroforestry systems to litter carbon stock has been reported by several studies. Based on study undertaken in Costa Rica, Ha¨ger (2012) and Hergoulac´h *et al*. (2012) recorded a litter carbon stock of coffee agroforestry that varied from 0.7 -1.7 and 4.8 t C ha^{-1}, respectively. Correspondingly, a research carried out in Ethiopia by

Melese *et al*. (2012) recorded huge variations in litter carbon stock (0.22 - 19.52 t C ha^{-1}) of coffee-based agroforestry systems.

2.1.4. Carbon trading

Continuous increase in the concentration of greenhouse gases in the atmosphere, mainly due to anthropogenic activities, has threatened to cause global warming. In order to reduce the negative impacts of this global warming, most governments have reached consensus to reduce emissions or raise sinks or sequestration of these greenhouse gases. Improving energy efficiency of existing engine technology and proper fossil fuel utilization, CO_2 sequestration, and facilitating the uses of unconventional fuels such as bio-hydrocarbon and biodiesel are often quoted as possible mitigation strategies for offsetting excess CO_2 emissions (Bharti *et al*., 2014). As pointed out by Kumar *et al*. (2018), forest preservation, tree planting, and improved, conservation-oriented agricultural management could help in sequestering about 110 billion tonnes of carbon over the next 50 years. In the early 1990s, the issue of trading the carbon sequestered emerged as an attractive and low cost means of mitigating climate change. To this effect, different protocols (e.g., The Kyoto Protocol) and agreements (e.g., The Paris Agreement) were developed. One of these mechanisms is carbon trading which includes emissions trading systems (ETSs), offset mechanisms, carbon taxes, and results-based climate finance (RBCF) (World Bank and Ecofys, 2018). In the carbon trading, those who reduce emissions or sequester carbon receive payments and those who have to decrease emissions can buy carbon credits to offset their emissions (FAO, 2010; Dilip, 2016).

The Kyoto Protocol is called Clean Development Mechanism. This mechanism allows the industrialized countries to compensate for their emissions by investing in carbon sequestering projects in developing countries (UNFCC, 2003, cited in Reda, 2017). The mechanism presupposes that carbon sequestration through activities related to the forestry sector could mitigate global warming. The Kyoto Protocol sets quotas on the amount of greenhouse gases that countries can produce. Countries, in turn, set quotas on the emissions of business. Business organizations that are over their quotas must buy carbon credits for their excess emissions. On the other hand, those organizations that are below their quotas can sell their remaining credits. Carbon can be traded through either the regulatory compliance or voluntary markets (FAO, 2010). The regulatory market is implemented through Clean Development Mechanism (CDM), Joint Implementation (JI) and the EU Trading System (ETS). Some of those countries who have not signed the Kyoto Protocol adopted national and regional GHG reduction programs (Chomba and Minang, 2009).

Similarly, the 2015 Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC) set a target to limit global warming to well below 2 °C above pre-industrial levels, with an aspiration target to limit warming to 1.5 °C (Climaloop, 2015). The price of a GHG is set in tonnes and to find a common unit for this commodity all GHG are converted to CO_2 equivalent (Baalman and Schlamadinger, 2008; Dilip, 2016). Hence, the price is set for one tonne of carbon dioxide equivalent. In connection with this, recent IPCC reports released in 2018 have provided price ranges for carbon trading (World Bank and Ecofys, 2018). These prices range from US$135–6,050/t$CO_2$e in 2030, US$245–14,300/t CO_2e in 2050, US$420–19,300/t CO_2e in 2070, and US$690–30,100/t CO_2e in 2100. However, the current prices are far below these figures and range from less than US$1/t CO_2e to a maximum of US$127/t CO_2e (World Bank and Ecofys, 2018). Furthermore, most jurisdictions still have carbon prices that are lower than those needed to cost-effectively deliver on the Paris Agreement (Clément *et al*., 2017; World Bank and Ecofys, 2018). According to the World Bank and Ecofys (2018) report, carbon prices of at least US$40–80/t CO_2 by 2020 and US$50–100/t CO_2 by 2030 are required to cost-effectively meet the temperature targets of the Paris Agreement. Carbon pricing initiatives implemented and scheduled for implementation cover 11 x 10^9 t of carbon dioxide equivalent or about 20 percent of GHG emissions.

Africa's share has remained at about two per cent of CDM projects officially registered with the UN's climate change secretariat (World Bank, 2010). The major countries registered are South Africa and some North African countries. With exclusion of these countries, participation of other countries remained at 0.6% (UNEP, 2010). Out of 424 million CERs (CDM credits) issued by August 2010, Africa's share was only 6 million of which 80% has gone to a single industrial gas plant in Egypt (IGES, 2010). The contribution of sub-Sahara Africa (SSA) to global emissions is relatively small; there is potential for SSA to contribute to climate-change mitigation, particularly in the forestry and agriculture sectors.

Regardless of the challenges in implementing and scaling-up carbon trading across the globe, many reports have clearly indicated its potential in mitigating climate change (IPCC, 2001;

UNFCCC, 2003; Fenhann, 2005; Reda, 2017; World Bank and Ecofys, 2018). As indicated in most of these reports, the advantages of carbon sequestration and trading include sustainable development through increased income, biodiversity conservation, and ecological restoration. As a result of these potential advantages, governments are increasingly recognizing carbon pricing as a key policy instrument to meet climate mitigation targets (World Bank and Ecofys, 2018).

2.2. Land Suitability Evaluation

2.2.1. Introduction

Broadly, land suitability is defined as "the fitness of a specific area of land for a specified kind of land use, called land utilization type (LUT), under a stated system of management" (FAO, 1976; Dent and Young, 1981; Sys *et al*., 1991a, b; Davidson, 1992; Singha and Swain, 2016). Similarly, Akinic *et al*. (2013) defined land use suitability evaluation or assessment as the process of determining the suitability of a given land area for a certain type of specific use (e.g., agriculture, forest, recreation, etc.) and level of suitability (e.g., highly suitable, moderately suitable, marginally suitable or not suitable). On the other hand, some scholars (e.g., Collins *et al*., 2001) view land suitability as a kind of analysis that is used to determine the most suitable tract of land for establishing new land uses, usually among multiple, competing uses. The assessment in question, as pointed out by Bandyopadhyay *et al*. (2009), should identify the opportunities and constraints, and, based on the identified opportunities and limitations, indicate ways for best use of a given land area. The same authors demand that, in addition to the inherent properties of a given unit of land, other relevant criteria, such as the socio-economic and environmental costs, consequences must be taken into consideration to support the long-term use of a piece of land on a sustainable basis. The presence of these various and multiple criteria makes land suitability analysis increasingly complex.

Because land suitability evaluation is carried out for different land uses, He *et al*. (2011) specifically defined agricultural land suitability evaluation as the process of assessment of land performance when used for alternative kinds of agriculture. More specifically, from crop production point of view, land suitability refers to the ability of a portion of land to tolerate the production of crops in a sustainable way (AbdelRahman *et al*., 2016). FAO during different time periods (e.g., FAO, 1976, 1983, 2007) highlighted that continuous utilization of agricultural land in the last many decades, without considering the capacity of the land, has caused much more destruction than provide the resources and has called for proper evaluation based on agriculture land use planning to curb this problem. In fact, land evaluation methodologies have shifted from broad based to specific assessment, with increasing use of quantification (Elsheik *et al*., 2010; Elsheik *et al*., 2013).

Dadhich *et al*. (2017) argue that the most pressing challenge facing farmers for the last many years has been matching suitable crops with specific land and climate they are operating in. Therefore, global trends clearly indicate that increased food demand and the shortage of land resources can only be matched through effective land suitability evaluation that provides the necessary input for developing rational land use planning and management (Yang *et al*., 2007; Ahmed *et al*., 2016; Ahmadi *et al*., 2017; Estrada *et al*., 2017; Hamere and Teshome, 2018; Worqlul *et al*., 2019). Because every crop requires specific agro-climatic conditions for its effective and optimal growth (Sys *et al*., 1991a; Haggar *et al*., 2011; Silva *et al*., 2013; Wang *et al*., 2015), the land evaluation must be carried out on the basis of integration of relevant land qualities and climatic conditions (Alemmeta, 2015; Al-Mashreki *et al*., 2015; Shirgire *et al*., 2017).

Land suitability analysis can answer the questions 'which land use is to apply under certain conditions' and 'where is the best site to apply this land use' (FAO, 1976; Ziadat and Sultan, 2011; Rabia and Terribile, 2013). Hence, suitability refers to the adaptability of a given area for a specific kind of land use in its present condition or after improvement (FAO, 1976; Gong *et al*., 2012; Pan and Pan, 2012; Singha and Swain, 2016). Besides, land-use decisions are not made just on the basis of land suitability but also according to the demand for products and the extent to which the use of a particular area is critical for a particular purpose (FAO, 1993). This indicates that the improper allocation of land use results in low productivity, generating processes of land degradation and, consequently, decreasing the sustainability and competitiveness of the land use systems (Elaalem *et al*., 2011; Ahmed *et al*., 2016). Therefore, for land to be selected for a particular purpose, it must address issues related to productivity, suitability, and potential degradation that may result from the management of such land (Olaniyi *et al*., 2015). Hence, land suitability evaluation is required to address issues related to productivity, suitability, and potential degradation of land management (De la Rosa *et al*., 2004; Ziadat and Sultan, 2011).

Nowadays, it is almost mandatory to guide land occupation according to its limitations and potentials. Achieving high productivity and environmental sustainability can be realized through appropriate land use decisions (Keshavarzi *et al*., 2011; Abagyeh *et al*., 2016; Mousavi *et al*., 2017). Theoretically, the potential of land suitability for agricultural use is determined by an evaluation process of the climate, soil, water resources and topographical, as well as the environmental components under the criteria given and understanding of the local biophysical restraints (Wang and Li, 2006; Mashayekhan and Mahiny, 2011; Bagherzadeh and Gholizadeh, 2016). The suitability is a function of crop requirements and land characteristics and it is a measure of how well the qualities of land unit match the requirements of a particular form of land use (FAO, 1976). This makes land suitability assessment a typical example of a multi-criteria evaluation (MCE) approach (Reshmidevi *et al*., 2009).

2.2.2. Why land suitability evaluation?

Land resources are limited and finite. By 2050, the world needs to double its crop production to feed the ever-growing population (Tomlinson, 2013). Under such circumstances, wise land use becomes a necessity for a healthy and prosperous future for the human race. Although prosperous future requires production of at least sufficient food, in many developing countries this is becoming increasingly challenging because land well-suited for the production of food is already in short supply, increasing competition for the limited resource among sectors (Zabel *et al.*, 2014; Mousavi *et al*., 2017). This unhealthy competition among sectors, coupled with the use of incompatible management practices, is largely responsible for the immense degradation, through various processes, of land resources (FAO, 2012; Briassoulis, 2019).

Further, natural, and complex interactions of social, economic, and political conditions are limiting the land's suitability for agriculture and cultivation practices (Zable *et al*., 2014). Nowadays the growing human population is forcing extensive use of natural resources that lead to land use/land cover changes (LULCC) (Hamere and Teshome, 2018). Such conversion of the natural system into managed system has led to degradation of natural resources (Aguiar *et al*., 2007; Bajocco *et al*., 2012; Jolejole-Foreman *et al*., 2012; Binyam, 2015), which affect the social, economic and environmental situation of the society. Land degradation and climate related factors have reduced availability of and accessibility to productive lands (Lal, 1994; Schmitz *et al.*, 2014; IPCC, 2018). Among the main reasons for the ever increasing degradation of land in most parts of the world is inappropriate use of land; use that does not consider the suitability and capacity of land for a given purpose (Gebresamuel *et al*., 2010; Eleni *et al.*, 2013; Binyam, 2015). Hence, the production of goods needed by people combined with the conservation of the natural resources on which that production depends so as to ensure continued production in the future is needed (FAO, 1993). Unwise use of land and its resources on one hand and the issue of sustainable agricultural production on the other is becoming a big concern at local and global scales (Gong *et al*., 2012; Singh, 2012). If efforts are not made to match land types with land uses in rational way, sustainable production will be constrained, ecosystem will be degraded and civilization may be collapsed. Hence, appropriate land use practices are not optional to address the ever-increasing demands of the human being now and in the future on a sustainable basis (Zomer *et al*., 2008; Mousavi *et al*, 2017).

Under conditions of dwindling land area suitable for agriculture, one of the most obvious and immediate solutions is to move the agricultural production to other available land or land currently used for other purposes in order to meet global food demand (Ramankutty *et al.*, 2006; Lambin and Meyfroidt, 2011; Schmitz *et al.*, 2014). Nevertheless, before the new land areas are put under agricultural production, their suitability for that specific use must be assessed. Land evaluation, a process of predicting land performance over time according to the specific types of use (Sonneveld *et al*., 2010; Suheri *et al*., 2018), is, therefore, a requisite to the decision-making processes involved in developing land use policies that will support sustainable rural development (Ahmed *et al*., 2016**)**. Generally, evaluation of a parcel of land for diverse uses is important to determine its level of capacity to support different purposes now and in the future on a sustainable basis. In consent with this, Akinc *et al*. (2013) pointed out that rational and sustainable use of land resources is among the most important indicators of economic growth. The World Commission on Environment and Development, in its part, clearly highlighted the importance of land suitability for sustainable development (Feizizadeh and Blaschke, 2012). AbdelRahman *et al*. (2016) argue that carrying out scientific land suitability evaluation is the prime requirement to reduce human influence on natural resources and guide decisions on optimal utilization of resources. Bandyopadhyay *et al*. (2009) also indicated that the knowledge of land suitability is an essential prerequisite for land use planning and sustainable development. Rational land use planning guides decisions on land use in such a way that the resources of the environment are put to most beneficial use for man, while at the same time conserving those resources for the future (Venugopal, 2009).

Land suitability analysis, on the other hand, is a tool used to identify the most suitable places for locating future land uses (Collins *et al*., 2001; Mohana *et al*., 2009). Land suitability evaluation, therefore, is an important step towards assessing the value and proficiency of the land and helps in planning for future sustainability of land resources, which in turn provides better results for facilitating development of management plans (Dent and Young 1981; Rabia and Terribil, 2013). In special reference to agriculture, the principal purpose of agricultural land suitability evaluation, defined as the process of assessment of land performance when used for alternative kinds of agriculture (He *et al*., 2011), is to predict the potentials and limitations of the land for crop production (Pan and Pan, 2012; AbdelRahman *et al*., 2016). Similarly, finding optimal locations for crops can increase economic benefits, as well as reduce negative environmental consequences (Ashraf *et al*., 2010). Hence, proper recognition of land abilities and allocation of them to the best and most profitable and stable use has a profound impact on sustainability of a system. Land suitability is thus a useful fundamental factor in the management of the environment (Vargahan *et al*., 2011). The principal objective of land evaluation is to select the optimum land use for each defined land unit and the conservation of environmental resources for future use (van Ranst and Debaveye, 1991; AbdelRahman *et al*., 2016). In summary, land suitability evaluation can contribute towards better land management, mitigation of land degradation, and designing land use pattern that prevents environmental problems through segregation of competing land uses. Suitability analysis allows identifying the main limiting factors for the agricultural production and enables decision makers to develop crop managements able to increase the land productivity (Mazahreh *et al*., 2018). Cognizant of this, most developing countries view land suitability evaluation as the main process for selecting crops adapted to soil and climatic conditions of their country (Zadeh *et al*., 2012).

Agriculture is the mainstay of the Ethiopian economy, contributing 41.4% of the country's gross domestic product, 83.9% of the total exports, and 80% of all employment in the country (Matousa *et al*., 2013). Furthermore, large proportion of the rural population inhabits the highlands. Further increase in the country's population is putting extra pressure on the already degraded agricultural lands (Hurni, 1993; Gashaw *et al*., 2014; Binyam, 2015). As a consequence, agricultural productivity remains far below its potential (Lal, 1994; Engda, 2009; Gashaw *et al*., 2014). In addition to the land degradation, the looming climate change is exacerbating the challenges the country is facing. The traditional practices are not coping with the current changes anymore. Like in all other parts of the world, an alternative approach to the current land use is required. Area specific investigations (Teshome *et al*., 2013; Yitbarek *et al*., 2013; Ayalew, 2014; Gizachew, 2014; Selassie *et al*., 2014; Agidew, 2015; Girma *et al*., 2015; Gizachew, 2015; Hailu *et al*., 2015; Nahusenay & Kibebew, 2015; Liambila & Kibret, 2016; Motuma *et al*., 2016; Worqlul *et al*., 2017) have been made to assess agricultural land suitability across different parts of Ethiopia. However, these studies did not do the suitability evaluation to identify land uses that might sequester high amount of carbon under future climate.

To date, there are different approaches to land suitability evaluation, each having different data requirements and different qualities of prediction. However, most of them have their basis on FAO Framework for Land Suitability Evaluation. There are no well-established rules about the adequacy of a given approach. Therefore, in developing countries, such as Ethiopia where inadequate data on land resources exist and funds are scarce to do detailed data analysis, qualitative physical land suitability evaluation methodology may be used, which may later be complemented with more complex quantitative methods. It was against this background that the physical land suitability approach was used in this study.

2.2.3. Characterization of land resources for land suitability evaluation

Appropriate land use decisions for achieving optimum productivity and ensure environmental sustainability of cultivated lands requires collection of land information upon which the decisions would be based (Keshavarzi *et al*., 2011). Estimation of quantity and quality of an ecosystem and the suitability of these resources for a certain range of land uses is needed in order to assure its future productivity and biodiversity's sustainability (Kilic *et al*., 2005). In line with this, Amiri and Shariff (2012) pointed out that land suitability evaluation should consider land properties and user needs that determine the most suitable land use type. This process is essential because the prime objective of land suitability evaluation is to enable decision makers prepare land use plans that enable the transfer of natural resources to future generations and that enable the planned and sustainable use of these resources in a manner that is suitable for their potential (Akıncı *et al*., 2013). While considering these attributes of land, i.e., climate, soil and landscape, the assumption made is that these factors affect potential productivity of a given crop (FAO, 2007) provided that other management aspects are maintained at optimum level.

Major soil and landscape attributes on which information needs to be collected and evaluated include topography (slope and elevation), soil physical properties (bulk density, soil texture, structure, soil depth, coarse fragments, and others) and soil chemical properties (pH, exchangeable bases, organic carbon, cation exchange capacity, salinity, alkalinity and others). As indicated by AbdelRahman *et al*. (2016), suitability evaluation allows identification of the main limiting factors for the agricultural production and enables decision makers to develop crop managements that are able to increase the land productivity. In connection with this, these same authors defined land suitability from crop production perspective as the ability of a portion of land to tolerate the production of crops in a sustainable way, clearly indicating the importance of adapting crop growth to the potentialities and constraints of local agro-ecologies as a key principle of sustainable land management. In the following sub-sections, a brief description of climate and, soil and landscape attributes for land suitability evaluation is presented.

2.2.3.1. Topography

The most important elements in topography are relief/slope and elevation. The relief is related to land management and erosion hazard and elevation is related to temperature and solar radiation and thus closely linked to plant requirements (Ritung *et al*., 2007). Topography-related soil variability is the result of the processes of surface and sub-surface water flow and erosion and deposition distributions in the landscape (Daniels and Hammer, 1992; Lark, 1999; Kumhalova *et al*., 2008). Consequently, topography influences the potential land use systems through long-term soil formation and short-term seasonal effects (Liu *et al*., 2007).

2.2.3.2. Soil

As soil resources are highly variable natural resource of an area, much of the information for physical land suitability evaluations is based mainly on soil survey results (Dent and Young, 1981). Therefore, soil data are of primary need necessary as a first step in sustainable land use and soil management decisions (Chukwu, 2013). The soil suitability assessment shows the suitability of the soil for growth of a particular crop. For this, the soil parameters ("land qualities") such as oxygen availability, nutrient availability, nutrient retention, rooting conditions, flood hazard, and sodicity are matched with the corresponding crop requirements. Similarly, soil depth influences nutrient availability, moisture storage and it also gives physical support for plants.

Plants need to take in oxygen through their root system and suffer restricted growth or ultimately death if deprived of oxygen. According to FAO (1983), oxygen availability restricts either due to excess rainfall than plants require, limited runoff or infiltration and percolation and/or presence of groundwater table. Flood hazard may occur due to standing water (inundation) and moving water (Sys *et al*., 1991a). The standing water affects oxygen availability in plants' root zone whereas the moving water physically damage plants. Rooting condition is affected by soil structure, texture, coarse fragment and bulk density (FAO, 1983) and is evaluated with effective depth, content of coarse fragment and wet and dry top soil consistence (FAO; 1983; Radcliffe, 1989; Sys *et al*., 1991a). Soil nutrient content is the simplest and most common method of assessing nutrient availability. Further soil parameters such as pH, available P, organic carbon, CEC, total nitrogen, total exchangeable bases (TEB), and texture are also considered to evaluate the nutrient availability and fertility condition of a soil (FAO, 1983; Sys *et al*., 1991a). Hence, all minor and major land improvements are required to improve the "quality" of the soil including but not limited to soil conservation, fertilization, deep ploughing, stone clearance, surface leveling, etc.

2.2.3.3. Climate

Climate is among the most important factors determining the sustainability of agricultural production systems (Neamatollahi *et al*., 2012) because of its direct and indirect influences on agriculture. Elements of climate, such as precipitation, temperature, solar radiation, wind, relative humidity, and others affect crop growth significantly. Some authors (e.g., Bernard, 1992) used the concept 'climate fertility' to describe the direct link between agricultural production potential and climate. As such, climate as a resource contributes to the general production potential of the globe (Gommes and Fresco, 1998) and should be regarded as the driving variable for exploitation of plant and water resources. In land suitability evaluation, climate is among the most important diagnostic criteria considered. It determines the length of growing period (through either supply of water or temperature or both) and the type of crops to be grown. Solar radiation, temperature, precipitation, wind, and relative humidity are some of the major parameters considered in land suitability evaluation as these attributes affect crop water requirement (evapotranspiration) and the supply of photosynthetically active radiation (PAR). If all other growth determining factors are optimum, the PAR determines to what level a crop attains or expresses its yield potential.

2.2.4. Basic terminologies used in land suitability evaluation

2.2.4.1. Land utilization types

Land utilization type (LUT) comprises specific types of land uses identified in terms of a crop or a combination of crops (FAO, 1976, 1983). Thus, a 'LUT is a kind of land use described or defined in a degree of detail that is greater than a major kind of land use' (FAO, 1976). They are described with as much detail and precision as the purpose requires. Therefore, LUTs are not a categorical level in a classification of land use, but refer to any defined use below the level of the major kind of land use (FAO, 1976). LUTs should not only define the crop or crop rotation (produce), but in addition it has to precise how to farm these crops (management). This implies that the concept "Land Utilization Type" includes the kind of crop, the succession of crops in a rotation or farming system with precision of management type (Sys *et al*., 1991a).

A land utilization type consists of a set of technical specifications in a given physical, economic and social setting (FAO, 1976). It could be the present or future modified environment. This may be the current environment or a future betting modified by major land improvement. Attributes of LUT include data or assumptions on intended output, level of production, skill required, market orientation, capital, infrastructure, etc. It is well noted that management practices on different areas within one LUT are not necessarily the same. Examples of LUT are rainfed agriculture of specific crops, land allocated for national park, plantation forest owned by government, etc. Land utilization types are fixed early in the evaluation and described in a generalized manner and subject to successive refinement in the course of the study (FAO, 1983).

Sometimes an appropriate LUT can be found by making several land mapping units part of the same management unit. They are defined for the purpose of land evaluation. Their description need not comprise the full range of farm management practices, but only those related to land management and improvement. At detailed levels of evaluation, closely defined LUT can be extended into farming systems by adding other aspects of farm management (FAO, 1976).

2.2.4.2. Land use requirements

Requirements of the land use refer to the set of land qualities that determine the production and management conditions of a kind of land use or conditions required for the successful operation of the LUT (FAO, 1976). As pointed out by Sys *et al*. (1991a) there is a need to establish, for each LUT, conditions that are best for its operation, the range of conditions which are less optimal but still acceptable, and conditions which are unsatisfactory. This is extremely important since different LUTs require some kinds of specific conditions of land for achieving their intended objectives successfully. For instance, crop requirement includes chemical properties of soil, climatic condition of an area, and management requirements. Land use requirements are expressed either based on land qualities or characteristics, or a combination of both (FAO, 1985). Thus, the degree to which the land use requirements are met by land mapping units for each land utilization types are rated on a scale ranging from highly suitable to unsuitable (Mohammed, 2003). Similarly, FAO (1983) recognizes four classes of factor ratings identified as highly suitable (S1), moderately suitable (S2), marginally suitable (S3) and not suitable (N).

FAO (1983) recognizes three sets of LURs for efficient functioning of a land utilization type, namely crop requirements, management requirements, and conservation requirements. The crop requirements refer to the physiological requirements of a crop or crops; management requirements pertain to technology of management systems, and conservation requirements are the requirements meant for avoidance of soil erosion or degradation. FAO (1983) and Rossiter (1996) listed four criteria that need to be considered while establishing land use requirements for a given LUT: (1) importance for the use; (2) existence of critical values in the study zone; (3) availability of data with which to evaluate the corresponding land quality or characteristics; and (4) availability of knowledge with which to evaluate the corresponding land qualities and characteristics.

2.2.4.3. Land characteristics

A land characteristic (LC) is an attribute of land that can be measured or estimated (FAO, 1976). More comprehensively, Sys *et al*. (1991a) and FAO (1983) defined land characteristics as measurable properties of the physical environment which are used for distinguishing between land units of different suitability for use and employed as a means of describing land qualities (LQs). Land characteristics, through their direct effect or influence on land qualities, are known to affect suitability in several different ways. As an example, the LC 'soil texture' has direct or indirect effect on some 14 LQs such as moisture availability, nutrient retention, workability, erosion hazards, etc. It is thus impossible to say that any particular texture is 'good' or presents 'no limitation'; sandy textures are favorable regarding workability but adversely affect moisture availability and nutrient retention (FAO, 1983).

The FAO Framework does allow the use of land characteristics directly to assess suitability, but it is generally clearer to use LQ as an intermediate level of evaluation, both because the total complexity of the problem is broken down into more manageable units, and because LQs in themselves provide useful information to the land evaluator (Rossiter, 1996). The challenge faced when LCs are used for land evaluation is related to the interaction of the LCs themselves.

2.2.4.4. Land qualities (LQs)

Land quality is defined as a complex attribute of land, which acts in a manner distinct from the actions of other land qualities in its influence on the suitability of land for a specific kind of use (FAO, 1983). The land quality could be either directly observed in the field or estimated based on land characteristics (FAO, 1976, 1985). Indeed, land qualities cannot generally be measured directly, but they can be estimated through measurement of land characteristics. A land quality is not necessarily restricted in its influence to one kind of use. The same quality may affect, for example, both arable use and animal product. There are a very large number of land qualities, but only those relevant to land use alternatives under consideration need to be determined.

A land quality is considered relevant to a given type of land use if it influences either the level of inputs required, or the magnitude of benefits obtained, or both. Although FAO (1983) allows the use of either land characteristics, land qualities, or a mixture of the two for assessment of land suitability, assessment based on land qualities is preferred, for land qualities are directly related to the specific requirements of land use. Land qualities take account of interaction between environmental factors and the total number of land qualities are relatively lower than land characteristics.

2.2.4.5. Diagnostic criterion

A diagnostic criterion is the qualities or characteristics employed to determine limits of land suitability classes or subclasses. It is a variable which has an understood influence upon the output from, or the required inputs to, a specified use, and which serves as a basis for assessing the suitability of a given area of land for that use. This variable may be a land quality, a land characteristic, or a function of several land characteristics. For every diagnostic criterion, there will be a critical value or set of critical values that are used to define suitability class limits (FAO, 1976).

2.2.5. Methods of evaluating overall physical land suitability (matching)

Physical land evaluation involves the evaluation of land based on physical parameters (Dent and Young, 1981; Smit *et al*., 1984). It assumes that permanent physical land resources determine land use and considers that physically limited land is also economically unprofitable and ecologically unsustainable. Physical land suitability evaluation can contribute towards better land management; mitigation of land degradation; and designing land use pattern that prevents environmental problems through segregation of competing land uses (Ziadat and Al-Bakir, 2006).

Although there are different ways of evaluating LCs and LQs, the FAO Framework recognizes two broad methods for physical land suitability evaluation. These methods are methods based on relative limitation scale and parametric approach (FAO, 1983).

The relative limitation method is a way of expressing the land characteristics or land qualities in a relative evaluation scale in which limitations are viewed as deviations from the optimal conditions of a land characteristic/land quality, which adversely affect a kind of land-use (Sys *et al*., 1991a). Recognized levels in the degree of limitation include no, slight, moderate, severe, and very severe limitations. Under the relative limitation method, there are two sub-methods, simple or maximum limitation and limitation based on number and intensity of limitations, for defining the suitability cases (FAO, 1983; Sys *et al*., 1991a). The limitation approach is the simplest method and one which has logic in its support, is to take the least favorable assessment as limiting. This method is a broadening of the 'law of the minimum' in agriculture, which states that crop yield will be determined by the plant nutrient in lowest supply. It is the simplest method which takes the least favorable as limiting (FAO, 1983).

The parametric method, on the other hand, consists in a numeral rating of the different limitation levels of the land characteristics in a numerical scale from a maximum (normally 100) to a minimum value. If a land characteristic is optimum for the considered land utilization type, the maximum rating of 100 is attributed, whereas a minimum rating is applied if the land characteristics are unfavorable (Sys *et al*., 1991a). The Storie and Square Root methods are the two sub-types used for assigning suitability classes in this parametric approach.

2.3. Biomass Production and Carbon Sequestration under Climate Change

2.3.1. Introduction

Climate change and agriculture are interrelated processes whereby climate variability and change directly affects agricultural production. Agriculture by nature is the most weather dependent of human activities (Ajibade, 2013; Hadgu *et al*., 2013). The increase in frequency of extreme climatological events, called climate change, has been influencing agricultural and food systems (Brown and Funk, 2008). Climate change projections such as changes in temperature, rainfall and severe weather events are expected to reduce crop yield in many regions of the developing world, particularly sub-Saharan Africa (Gornall *et al*., 2010). Agricultural production in sub-Saharan Africa is arguably the most sensitive to climate variability, given its repeated exposure to extreme climate events, very high reliance on rainfed agriculture for basic food security and economic growth, and entrenched poverty (IPCC 2014a; World Bank, 2015). In the region the impacts of increased temperature from global warming and changes in rainfall patterns resulting from climate change are expected to reduce agricultural production and put further pressure on marginal land (Travis and Daniel, 2010; FAO, 2011; Beddington *et al*., 2012; Valizadeh *et al*., 2013).

The seasonal development of temperature and rainfall determines the length of the growing season, the start of the growing cycle and the potential number of annual cropping. Thus, the option of multiple cropping represents an important measure for farmers to increase production (Zabel *et al.,* 2014). Changing climate does not only affect the suitability of land, but also the start and length of the growing cycle. Agriculture in cold-limited (high-latitude and high-altitude) areas could benefit from a modest temperature rise that increases the length of the growing season (Thornton *et al*., 2009). East African highlands are among the regions benefiting from such changes. Studies suggest that food crop production will increase slightly at high latitudes under moderate climate change, but strong negative shift in the suitability of cereal production is predicted by the 2080s (Fischer *et al.*, 2005; Parry *et al*., 2005). On the contrary, climatic changes projected for as early as 2030 could cause significant declines in maize yields (Lobell *et al.,* 2008a, b).

Maize, one of the staple foods in sub-Sahara Africa and covering about 27% of an area under cereals (Smale *et al*., 2011), will show a reduction in yield under future climate scenarios. For 1 °C rise in temperature above normal (25 °C), Easterling *et al*. (2007), Lobell and Field (2007), and Brown (2009) projected a 3, 8.3, and 10% reduction in maize yield.

Sorghum is another important crop in sub-Sahara Africa next to maize (Obalum *et al*., 2012). The crop has resistance to drought and high temperature. Studies, however, indicated that sorghum production would decrease by 8.4% (Lobell and Field, 2007) and 7.8% (Hatfield *et al*., 2008) for 1 °C increase in temperature. Some other studies projected slight increment (4%) in sorghum yield by 2020s and 2050s and slight reduction (2%) during 2080s in East Africa (Fischer, 2009). Hence, sorghum is less sensitive to climate change compared with maize.

Climate predictions from global circulation models, together with crop models, have been used to project future crop yield under different climate scenarios (Baron *et al*., 2005; Malone *et al*., 2009). Over the last 10 to 11 years, several models capable of simulating the aboveground crop biomass accumulation and the final crop yield with satisfactory accuracy for a variety of crops have been developed (Gassman *et al*., 2009; Raes *et al*., 2009; Steduto *et al*., 2009; Mancosu *et al*., 2015; Simionesei *et al*., 2016; Zhou *et al*., 2018). One of these examples is the international water-driven crop model developed recently by FAO, AquaCrop. AquaCrop has been widely used for accurate simulation of soil moisture, canopy cover, biomass and yield (Heng *et al*., 2009; Tavakoli *et al*, 2015; Linker *et al*., 2016; Toumi *et al*., 2016). Unlike other crop models (Jones *et al*., 2003; Stöckle *et al*., 2003; Keating *et al*., 2003), AquaCrop adopts a “K_c (crop coefficient) -ETo (evapotranspiration)" approach based on green canopy cover (CC) to calculate ET and its components (Steduto *et al*., 2009; Pereira *et al*., 2015b). Different authors also used AquaCrop model to simulate crop development (Geets *et al*., 2010), yield and crop productivity (Erkossa *et al*., 2011; Araya *et al*., 2015) and adaptation of sowing date (Alshikh *et al*., 2017).

Ethiopia, a country where about 85% of the total population is dependent on subsistent agriculture, is experiencing significant variations in spatial and temporal patterns of climate. According to National Meteorological Service Agency (NMSA) (2006), the country experienced 10 wet years and 11 dry years over the last 55 years analysed, demonstrating the strong inter-annual variability. The average minimum temperature has increased by about 0.37 ^{o}C for every ten years (NMSA, 2007) and the annual mean temperature has increased by 1.3 ^{o}C between 1960 and 2006 (McSweeney *et al*., 2008). Climate projection has indicated that Ethiopia will be more vulnerable to climate variability. According to IPCC (2014a), the four seasons of the nation will be warm with frequent heat waves. Rainfall, however, will be with more intense wet season and less severe drought during October-November-December and March-April-May. This inter-annual variability of climate has impact on biomass production and energy transfer at ecosystem level, which in turn affects the carbon sequestration potential of carbon pools. Hence, the livelihoods of smallholder farmers, who have low technical and financial capacity to adapt to and cope-up with the problem, will be at risk. Studies are also indicating the strong linkage between Ethiopian economy and climate performance (Grey and Saddoff, 2005; World Bank, 2005). Furthermore, the low productivity of the system aggravates land use/land cover changes in search for fertile and productive land, which mostly occurs at the expense of conversion of forest and grazing lands. Information regarding future impact of climate on biomass production of selected maize and sorghum cultivars is absent. Hence, this study was conducted to estimate the organic carbon stock and carbon sequestration potential of selected land use types under projected climate over the coming 50 years in Hades Sub-watershed, eastern Ethiopia.

2.3.2. Temperature trends and its impact on biomass production

Climate models projected an increase in mean temperature (Schär *et al*., 2004; Fischer and Schär, 2010). IPCC (2007) also reported expected changes in temperature over the next 30 -50 years to be in the range of 2 -3 °C. Globally, average annual temperatures are projected to rise by 0.3 to 2.5 °C by 2050, relative to the 1985 to 2005 average. In East Africa temperature projections range from approximately no change to 4 °C warmer conditions in both December, January and February (DJF) and June, July and August (JJA) seasons by 2050. Lower temperature increases are more likely under a low emissions scenario and higher temperature increases are more likely under a high emissions scenario (Daron, 2014). The same author reported that by mid-century different model simulations projected a warming in the DJF season of between 1 and 3 °C for northern regions of East Africa and between 1 and 2 °C elsewhere. In the JJA season, the pattern is similar but the south of the region also shows high levels of warming. According to IPCC Fourth Assessment Report (2007), the median temperature rise by 2080 is expected to range from 3.2 to 3.6 °C across Africa.

Temperature rise is likely to result in reduced food production within the next couple of decades in regions already facing food insecurity. For example, yields of major cereal crops (rice, wheat, maize, sorghum) in the tropics and subtropics are expected to decline with a temperature increase as small as 1 °C, such as could occur by around 2030. While adaptation measures could offset some of the expected productivity decline, impacts from a temperature increase of 3 °C or more, which may well occur by the end of the century, could result in a significant loss of productivity in low-latitude regions and diminish effectiveness of adaptation measures (Jon, 2009). Similarly, scientific evidences are predicting that higher temperature resulting from climate variability will further depress agricultural crop yield in many arid and semi-arid areas of Ethiopia over the coming decades (Bezabih *et al*., 2010). Hence, farmers in these areas will be more vulnerable to climate impacts as their economies depend largely on climate sensitive agricultural production system (Temesgen, 2000).

Daron (2014) simulated temperature patterns across East Africa until the 2040s using three climate models (HadGem2-CCLM4, ICHEC-CCLM4, and ICHEC-KNMI). The models projected a rise in temperature. From among the models, HadGem2-CCLM4 model projected the highest magnitude of increase by the 2040s with central regions of Tanzania, eastern Uganda, western Kenya, western Ethiopia and South Sudan expected to have an increase in average annual temperature that in some locations exceeds 3 °C. The changes projected by ICHEC-CCLM4 and ICHEC-KNMI models are less dramatic with most regions expected to warm by less than 2.5 °C by the 2040s. These two models projected higher warming in northern Ethiopia and Sudan.

The rate of photosynthesis and respiration increases with an increase in temperature, until a maximum value of photosynthesis is reached. The photosynthetic response to temperature is significantly related to crops' photosynthetic pathway (C3 or C4) (Pessarakli, 2005), though as a whole, photosynthesis rates increase linearly from a base temperature to a lower optimum and sharply decline with increasing temperature from an upper optimum (Sage and Kubien, 2007). It is well documented that the growth of higher plants is restricted to a temperature between 0 and 60 ºC, and crop plants are further restricted to a narrower range of 10 to 40 ^{o}C. However, each species and variety of plants and each age group of plants has its own upper and lower temperature limits. Beyond these limits, a plant becomes considerably damaged and may even be killed (Mavi and Tupper, 2004; Sage and Kubien, 2007; Barnabás *et al*., 2008). Hence, rate of plant growth and development is dependent up on the temperature surrounding the plant and each species has a specific temperature range represented by a minimum, maximum, and optimum (Hatfield and Prueger, 2015). For instance, the maximum production of dry matter occurs when the temperature ranges between 20 and 30 °C, provided moisture is not a limiting factor (Mavi and Tupper, 2004).

In areas where temperatures are already close to the physiological maxima for crops, such as seasonally arid and tropical regions, higher temperatures may be more immediately detrimental, increasing the heat stress on crops and water loss by evaporation (Gornall *et al*., 2010). The rise in seasonal mean temperature showed a strong negative impact on crop yield mainly by a reduction in the length of the growing season (Liu, 2010). The effects, however, vary depending on the characteristics of the crop, the timing of heat stress in relation to crop development, and the conditions under which it is grown. Large number of studies have demonstrated the impacts of high temperature on many plant processes. Mavis and Tupper (2004) and Sage *et al*. (2011) revealed that high temperature affects photosynthesis negatively, while Allakhverdiev *et al*. (2008) documented that respiration is equally affected negatively. Development rate (Wolkovich *et al*., 2012) and transpiration (Crawford *et al*., 2012) are the other plant processes known to be affected by high temperature with negative consequences. Similarly, reproductive development (Klein *et al*., 2007; Battisti and Naylor, 2009; Sacks and KucHarik, 2011; Hatfield and Prueger, 2015), dry matter partitioning (Zhao *et al*., 2013), and root growth (Singh *et al*., 1998; Mavi and Tupper, 2004) are influenced by high temperature.

2.3.3. Impact of rainfall on biomass production

Climate models projected a large variability of rainfall at global scale (Schär *et al*., 2004; Fischer and Schär, 2010). However, future projections of rainfall change are subject to substantial uncertainties and model simulations disagree on the likely direction and magnitude of change. In East Africa, variability in inter-annual, decadal and multi-decadal time scales are expected to continue to be the dominant influence on future rainfall. However, towards the end of the 21st century, there is a tendency of models to predict a shift to slightly wetter conditions on average over East Africa, especially for the high RCP8.5 emissions scenario, whilst some models project drier average conditions (Daron, 2014). Over 80 percent of the global agriculture is rainfed. Hence, current and projected rainfall has impact on agricultural crop production (Olesen and Bindi, 2002; Reilly, 2003).

Climate projections have indicated that rainfall is likely to become increasingly aggregated. However, on an annual (seasonal) time scale, the number of rainfall events is likely to decrease, while rainfall intensity is likely to increase due to greater atmospheric moisture retention with increased air temperatures (Huntingford *et al*., 2005). In contrast to global models, regional climate models project no change, or even a drying for East Africa, especially during the long rains (Laprise *et al*., 2013). Some regional climate model study projects an increase in the number of dry days over East Africa (Vizy and Cook, 2012). Even in the absence of reduced mean rainfall, increased water stress could occur where higher temperatures in warm regions increase moisture losses from evapotranspiration. Warming of the atmosphere, changes in rainfall abundance, and frequency and severity of extreme events altogether will exert significant pressure on agricultural water use, with several regions currently experiencing water deficits (Jon, 2009). Hence, rainfall is not the only influence on water availability. Similar researches have indicated that increasing evaporative demand, owing to rising temperatures and longer growing seasons, could increase crop irrigation requirements globally between 5 and 20 percent, or possibly more, by the 2070s or 2080s (Fisher *et al*., 2006).

Rainfall variability has historically been a major cause of food insecurity and famines in Ethiopia (Woldeamlak, 2006). The amount and temporal distribution of rainfall is generally the single most important determinant of inter annual fluctuations in national crop production levels (Mulat *et al*., 2004). Such substantial inter-annual variability in the length of the growing season that was ranging from 76 to 239 days implies a challenge to rainfed agriculture (Kassie *et al*., 2013).

In general, the results of model predictions for rainfall across different parts of the globe clearly indicate that biomass production will be affected significantly under changing climate. The effect is going to be more significant in production systems that rely on natural rainfall heavily.

2.3.4. Carbon sequestration in agriculture

Agricultural production has profound impact on global carbon and estimated to have about 24% contribution to global greenhouse gasses emission (IPCC, 2007). The global soil carbon (C) pool is about 3.2 times the size of the atmospheric pool and four times that of the biotic pool (Lal, 2010). Cropland soil has the potential to sequester C and is thus important as a CO_2 sink (Smith *et al.*, 2000; Zomer *et al*, 2017). Globally, cropland stores more than 140 x 10^9 t C in the top 30 cm of soil, which is about 10% of the total global SOC pool (Paustian *et al*., 2016). Croplands can be one of the best options to enhance carbon sequestration in the soil since there are different options to improve their potential through better management. Past estimates indicated that 50 to 70% of soil carbon stock in cultivated soils has been lost (Lal, 2004). Hence, croplands have huge potential to sequester carbon until it reaches saturation point (Sommer and Bossio, 2014). Moreover, increasing the SOC content in soils does not only bring advantages from an agricultural point of view, but it is also seen as a way to mitigate climate change (IPCC, 2014a). Therefore, organic matter management, of which incorporation of crop residues is one, is important in increasing soil organic carbon and soil nutrient capital, improving soil structure and water retention, decreasing risk for erosion, and eventually improving the sustainability of production (Smaling, 1998; Lehtinen *et al.*, 2014; Liu *et al.*, 2014). Complete removal of residue resulted in a C loss while its direct incorporation into the field or transformation in to manure or sludge enhanced C content of the soil (Kätterer *et al.*, 2012). Furthermore, it was noted that manure application has greater effect on SOC sequestration than straw incorporation (Thomsen and Christensen, 2010). A study in northern part of Ethiopia (Kätterer *et al.*, 2012) indicated that the amount and quality of biomass being incorporated into the soil, the residue management, and the organic amendments were found to be governing factors for carbon sequestration in agricultural lands.

Lemke *et al.* (2010) indicated that removal of 22% of straw residue did not cause any significant effect on SOC. After reviewing long term researches, Lehtinen *et al.* (2014) reported 7% increment of SOC in Europe while Liu *et al.* (2014) reported 12.8% increment at global scale.

Carbon sequestration on agricultural lands is possible through a range of soil management strategies and could be substantial with widespread implementation (Daniel, 2015). Less attention has been given for the carbon sequestration potential of soil though it is one of the major carbon pools in the terrestrial environment (Geoghegan *et al.*, 2010; Daniel, 2015), with world's soils capable of storing approximately 2200 Gt (billion tonnes) of carbon in their top metre, two-thirds of it in the form of organic matter (Batjes, 1996). Therefore, finding ways to increase soil carbon in agricultural systems will be a major component of using soils as a sink.

2.3.5. Representative concentration pathways (RCPs) for climate projection

Because of the uncertainties surrounding prediction of climate change, it is common to employ climate scenarios for estimation of the impacts of climate change on a given system (Lamb, 1987). Socio-economic and emission scenarios are used in climate research to provide information on how the future may evolve with respect to a range of variables including socio-economic change, technological change, energy and land use, and emissions of greenhouse gases and air pollutants (van Vuuren *et al*., 2013). According to IPCC (2013), scenarios are defined as a plausible and often simplified description of how the future may develop based on a coherent and internally consistent set of assumption about deriving forces and key relationships. They should be considered plausible and illustrative, and do not have probabilities attached to them (Stocker *et al*., 2013). The RCPs were developed using Integrated Assessment Models (IAMs) that typically include economic, demographic, energy, and simple climate components. The emission scenarios they produce are then run through a simple model to produce time series of GHG concentrations that can be run in AOGCMs (Stocker *et al*., 2013).

Estimates of the equilibrium climate sensitivity (ECS) based on observed climate change, climate models and feedback analysis, as well as paleoclimate evidence indicate that ECS is positive, likely in the range of 1.5 to 4.5 °C with high confidence, extremely unlikely less than 1 °C (high confidence) and very unlikely greater than 6 °C (medium confidence) (Stocker *et al*., 2013).

The shift from Special Report on Emission Scenario (SRES) to RCPs scenarios emerged due to the need for more detailed information for running the current generation of climate models, increasing interest in scenarios that explicitly explore the impact of different climate policies and increasing interest in exploring the role of adaptation in more detail than that have been done so far (Moss *et al.*, 2010). Two important words, representative and concentration pathways, are emphasized in the RCP scenario. The word “representative” signifies that each of the RCPs represent a larger set of scenarios in the literature. The words “concentration pathway” are meant to emphasize that these RCPs are not the final new, fully integrated scenarios but instead are internally consistent sets of projections of the components of radiative forcing that are used in subsequent phases (van Vuuren *et al.*, 2013). Brief description of the RCPs is presented in Table 2.1.

Table 2.1: Overview of representative concentration pathways (RCPs)

RCP	Description	Publication—IA Model
RCP8.5	Rising radiative forcing pathway leading to 8.5 W/m^2 (~1370 ppm CO_2 eq and 2.6-4.8 ^oC) by 2100.	(Riahi *et al.*, 2007; IPCC 2013b)—MESSAGE
RCP6	Stabilization without overshoot pathway to 6 W/m^2 (~850 ppm CO_2 eq and 1.4-3.1 ^oC) at stabilization after 2100	(Fujino *et al.*, 2006; Hijioka *et al.*, 2008; IPCC 2013b) - AIM
RCP4.5	Stabilization without overshoot pathway to 4.5 W/m^2 (~650 ppm CO_2e and 1.1-2.6 ^oC) at stabilization after 2100	(Smith and Wigley, 2006; Clarke *et al.*, 2007; Wise *et al.*, 2009; IPCC 2013b) - GCAM
RCP2.6	Peak in radiative forcing at ~3 W/m^2 (~490 ppm CO_2eq and 0.3-1.7 ^oC) before 2100 and then decline (the selected pathway declines to 2.6 W/m^2 by 2100).	(van Vuuren *et al.*, 2006; Van Vuuren *et al.*, 2007; IPCC 2013b) -IMAGE

Approximate radiative forcing levels were defined as ±5% of the stated level inW/m^2 relative to pre-industrial levels. Radiative forcing values include the net effect of all anthropogenic GHGs and other forcing agents [Adapted after van Vuuren *et al*. (2011) and IPCC (2013)]

2.3.6. Modelling crop biomass production under climate change

Modelling crop growth can provide a powerful tool for evaluating the effects of environmental factors on crops (Rötter *et al*., 2015). Previous crop models, however, were developed for small area climate change impact studies and applied at small scale, with single crops and few management alternatives over limited seasons (Ewert *et al*., 2015). Now a days, however, several crop models are operating at large scale such as climate change impacts for larger areas

(Easterling *et al*., 2007) and models' flexibility improved to support the simulation of different crops, cropping systems, and production situations (Brown *et al*., 2014). The complexities of climate change impacts and actions required to adapt and mitigate the impacts of climate change are calling for more flexible and integrated assessment modeling (Laniak *et al*., 2013).

Through past efforts, various models that integrate factors and processes that affect plant growth in different ways have been developed and tested. Boote *et al*. (2013) used a crop model that integrates nutrient (C and N) and water balance from planting to maturity and provides estimates of final yield and biomass production, as well as, daily values of crop and soil components. Others used models for choosing optimum sowing/planting date (Rauff and Bello, 2015), creating an irrigation schedule (Tsakmakis *et al*., 2018), evaluating crop-weed interactions (Kropff and Van Laar, 1993), assessing climate change impacts on crops' yield (Voloudakis *et al*., 2015), and quantifying damage caused by pests (Kropff *et al*., 1995). However, regional models are expected to be simple with lower data demand and various aggregation methods (Angulo *et al*., 2013).

Under the changing world and the ever increasing demand for agricultural production, long term researches may not provide quick response for issues that are promptly needed. Hence, scientifically based crop growth models are useful to better understand and formulate innovative technologies related to agricultural crop production. AquaCrop is one of those models.

AquaCrop is an empirical process-based, dynamic crop-growth model developed to simulate biomass and yield response of herbaceous crops (i.e. field and vegetable crops) to water under varying management and environmental conditions (Vote *et al*., 2015; Zhou *et al*., 2018). Now a days AquaCrop is widely used for researches related to agricultural water management (Tavakoli *et al*., 2015; Linker *et al*., 2016; Toumi *et al*., 2016). "AquaCrop is a canopy-level and water driven model which simulates crop biomass and harvestable yield as constrained by available water" (Hsiao *et al*., 2009). The crop model derives crop productivity in relation to water stress, which so far was difficult relationship to include in crop modeling (Steduto *et al*., 2009). AquaCrop predicts biomass based on cumulative daily transpiration and the crop water productivity. Crop water productivity, which is defined as "crop yield/water consumptively used in evapotranspiration" (Kassam and Smith, 2001). The model was designed to be sufficiently accurate for the development of water management strategies while avoiding the complexity and lack of transparency that has been common among existing crop models.

In this chapter, literature review from previous related works on relevant topics of the research was presented. Now, the next chapter is devoted to description of methodologies followed and materials used while conducting the research.

CHAPTER THREE

MATERIALS AND METHODS

3.1. General Description of the Study Area

The study was conducted on major land uses of Hades Sub-Watershed in eastern Ethiopia. It is located at about 401 km from Addis Ababa along the highway to Dire Dawa and Harar cities. The geographical location of the sub-watershed is 9°18′0″ - 9°19′0″ North and 41°13′0″ - 41°15′0″ East (Figure 3.1). The altitude of the study site ranges from 1750 to 2775 meters above sea level (m.a.s.l.) and it covers about 971 ha area of land. The rainfall pattern is bimodal with the main rainy season occurring from June to September, while the short rainy season extends from February/March to April. The thirty three years (1980 – 2013) meteorological data indicates that the mean annual rainfall is 930 mm. The minimum and maximum temperature of the area is 10.3 and 18.9 °C, respectively. The Hades forest used to cover most of the present crop and grasslands and coffee agroforestry sites. Currently, the forest is degraded due to continuous disturbance. The remaining climax reaching and dominant tree species are *Afrocarpus gracilior*, *Croton macrostachyus*, *Hagenia abyssinica*, *Schefflera abyssinica* and *Prunus africana.*

The farming practice in the area is mixed farming whereby the farmers cultivate annual and perennial crops and manage livestock. The dominant agricultural crops are sorghum (*Sorghum bicolor L.),* maize (*Zea mays L),* barley (*Hordeum vulgare*) and coffee (*Coffee arabica*). Coffee is also an emerging cash crop introduced into the area. Recently, farmers have started growing some horticultural crops, such as potato (*Solanum tuberosum*), onion (*Allium cepa*), and cabbage (*Brassica oleracea*) using water emerging from springs from under the forest for irrigation. Intercropping, such as growing haricot bean under sorghum and maize with coffee shrub, is a common practice in the sub-watershed. Regardless of the quality, soil bunds are constructed on croplands and coffee agroforestry (Figure 3.2). However, bunds on croplands are frequently damaged by livestock.

Based on the geological map of Ethiopia (at 1:2 000 000 scale), Hades area is composed of various formations, including Alage, Adigrat, Hamanlei, Amba Aradom and Urandab formations. The geological map of the Wabi Shebelle basin (at a 1:1.000.000 scale) shows that the study area is made up of Trap series volcanic formation during Miocene age (NWRC, 1973). According to MWIE (2015), Alaji Basalts, which consist of porphyritic basalt lavas with large plagioclase and aphyric basalt lavas, were identified around the study area.

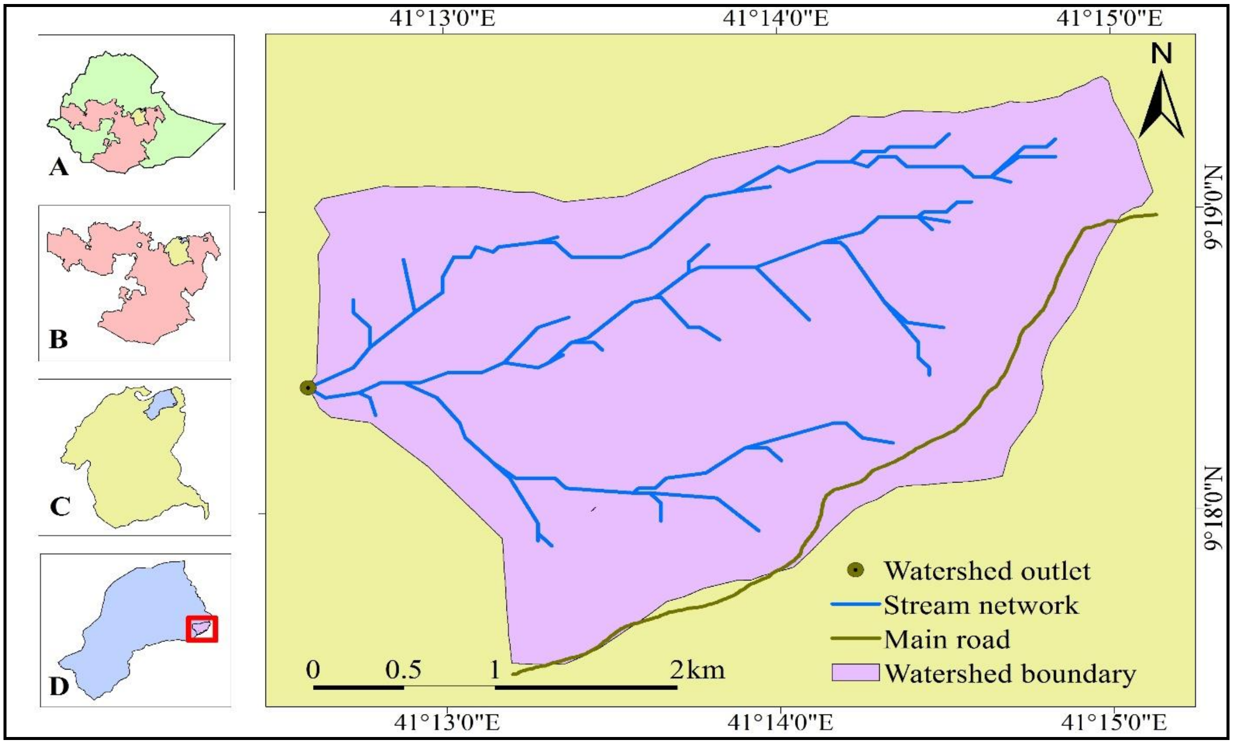


Figure 3.1: Location of the study site (A) Ethiopia; (B) Oromiya Region; (C) West Hararghe and (D) the study site within Doba *Woreda* (District).

Figure 3.2: Partial view of the study area (A) view inside the forest, (B) DBH measurment, (C) litter sample measurement, (D) farmland with physical conservation structures (bunds), (E) partial view of the study area and (F) soil auger observation at the field.

3.2. Carbon Stock Assessment

3.2.1. Delineation of major land uses/land covers of the study area

Candidate land use/land cover (LULC) categories were identified using topographic map (1:50000) obtained from Ethiopian Mapping Authority and Google Earth online imagery and Digital Elevation Model (DEM: 30 m x 30 m resolution). Following this, physical observation was made to confirm the basic information about the major land use types and topographic variations of the study area. The boundary of the sub-watershed was delineated using GPS recordings. The LULC map of the study area was produced in ArcGIS 10.4.1 software. Accordingly, four major land use types (cropland, grazing land, coffee agroforestry, and natural forest) were identified (Table 3.1).

Table 3.1: Description of the major current land uses identified in Hades Sub-watershed, eastern Ethiopia

Land use/area	Symbol	Definition
Cropland	CL	Cultivated land used for production of cereal crops. In this land use, the crop residue is collected, pilled, and used for animal feed, fuel, and, in some cases, for house construction and as source of cash.
Grazingland	GL	A land commonly used for open grazing and in some cases for cut and carry system. It is found scattered within the sub-watershed particularly in areas with impeded drainage.
Coffee agroforestry	CA	A land use characterized by presence of coffee under *Cordia africana* as shade tree with well-built soil conservation structure and frequently enriched with partially decomposed organic matter such as cow dung.
Natural forest	NF	Land covered with naturally grown trees and dominated by indigenous tree species that have reached climax whereby the understory vegetation is suppressed by the shade effect of the big trees. This land use is found mainly in the higher altitudes and steep slopes of the sub-watershed.

3.2.2. Sampling techniques

Sampling sites for sample collection were the strata that were determined based on the land use/land cover types. Two transects were established along the slope at 500 m interval crossing cropland, grazing land, coffee agroforestry, and natural forest guided by compass. Besides, random sample points were established in areas not covered by the transect (Figure 3.3). On crop and grasslands, sample plots of 10 m X 10 m were laid at 500 m interval. On coffee agroforestry, sample plots of 20 m X 20 m were used. A 'nested' sampling approach (Hairiah *et al*., 2001; Iqbal and Tiwari, 2015) was used for collecting both vegetation and soil samples in the natural forest. To avoid boundary effect, the first plot was established 150 m inside the forest to the border line. The locations of the sampling points were recorded using GPS.

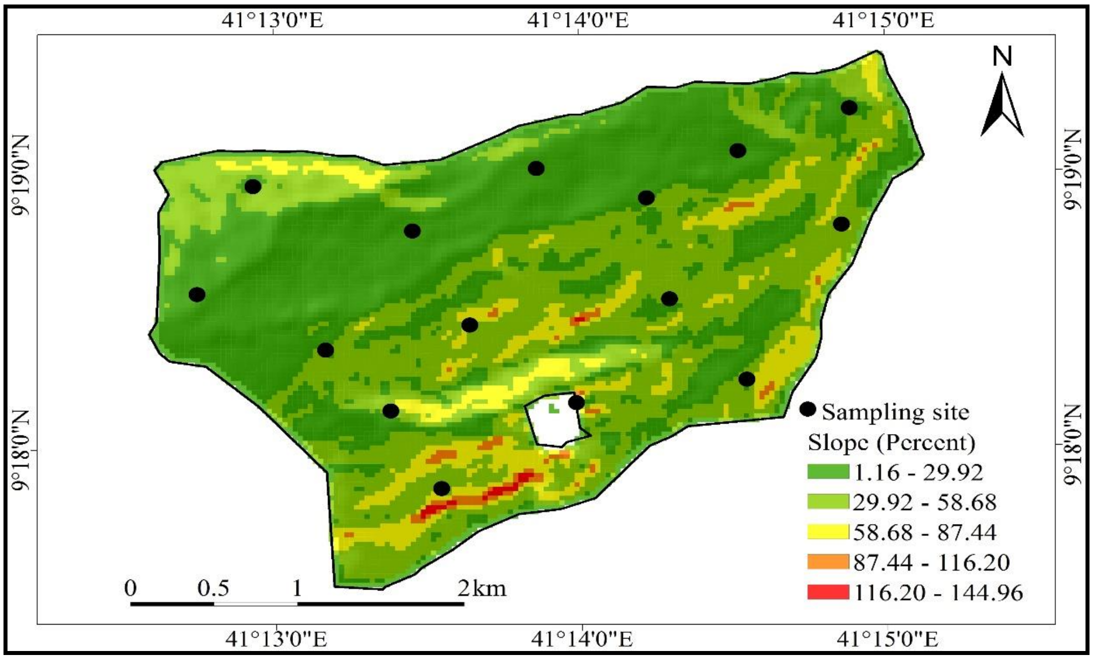


Figure 3.3: Hades subwatershed sampling sites and slope (in percent) map.

None distructive sampling approach was followed for above and below ground vegetation biomass estimation. In the sample plot, all living trees and shrubs with diameters at breast height (dbh) of ≥ 5 cm were inventorized. The dbh of the trees and shrubs were measured using diameter measuring tape (Pearson *et al*., 2007). All the litter samples in a 0.5 m x 0.5 m quadrat from the four corners and the center of 40 m X 5 m plot were collected and a composite sample was made. The aboveground carbon stock of coffee shrubs was estimated from the diameter measured at 40 cm from the ground using caliper (Pearson *et al*., 2007). As suggested by Santantonio *et al*. (1977), the belowground biomass (root) of a plant was calculated from the aboveground biomass. The sites that were used for aboveground carbon stock measurement were also used for belowground carbon stock measurement in both the natural forest and the coffee agroforestry.

Soil samples were taken from the four corners and center of the 40 m X 5 m sub plot for the natural forest and the 10 m X 10 m plot for the cropland, grazing land, and coffee agroforestry. The samples were taken from three depths (0-20, 20–40, and 40-60 cm) (Lemenih *et al*., 2005) in accordance with the standard set by IPCC (2003) for carbon accounting purpose. Hence, three composite samples per plot were collected for laboratory analysis of organic carbon, total nitrogen, soil texture, and pH. For bulk density determination, undisturbed soil samples were collected from the same depths using core sampler and from the center of the respective plots. All disturbed soil samples were air-dried, grinded, passed through a 2 mm mesh sieve for determination of the selected soil properties except organic carbon and total nitrogen in which case the samples were crashed further to pass through a 0.5 mm mesh sieve.

3.2.3. Laboratory analysis

For litter a sub sample of 100 g from a composite sample was oven dried at 105 ^{o}C until a constant weight was attained. Then after, a sample of 4 g was ignited in Muffle furnace (Carbolite Aston-Lan. Hope, England) at 500 ^{o}C for 8 hours (Campbell and Plank, 1998). For all the samples, the determination was made in triplicate.

Soil texture was determined by the Bouyoucos hydrometer method as described in van Reeuwijk (2002). The dry bulk density of the soils was determined using the core method as described in Blake and Hartge (1986) in which case the core samples were dried in an oven set at a temperature of 105 °C to a constant weight. The bulk density was obtained by dividing the oven dry weight by the volume of the respective cores as is indicated in Equation [11]. Soil pH in water was measured in soil–water (1:2.5) suspension using pH meter (McLean, 1982). The soil organic carbon content was determined following the Walkley-Black oxidation method (Walkley and Black, 1934). Total nitrogen was determined by the micro-Kjeldahl digestion, distillation, and titration method (Bremner and Mulvney, 1982).

3.2.4. Estimation of vegetation biomass and carbon

Species-specific allometric equations were not available for all trees of the study area. Therefore, the dry weight biomass of each tree was calculated using the following formula (Brown *et al*., 1997):

$$AGB = 34.4703 - 8.067D + 0.6589D^2 \quad [1]$$

where AGB is aboveground biomass in kg, D is diameter at breast height (dbh)

As described by Cairns *et al.* (1997), root biomass in ecosystems is often estimated from root-to shoot ratios. The ratio ranges from 0.18 to 0.30, with tropical forests in the lower range. As suggested by Santantonio *et al*. (1977) and Abyot *et al*. (2019), the belowground biomass (root) of a plant is close to 20 percent of its total aboveground biomass. Accordingly, the root biomass of trees was estimated using the following formula:

$$\text{Root biomass} = \text{AGB} * 0.2 \quad [2]$$

The corresponding carbon for above and below ground living biomass was obtained by dividing the biomass with 0.5 (Doetterl, 2015).

Litter (undecomposed and unburned fallen leaves, twigs, and branches) was collected from the natural forest and coffee agroforestry. Litter samples were collected from 0.5 m X 0.5 m quadrants for natural forest and 10 m X 10 m plots for coffee agroforestry. The biomass and carbon stock in litter were calculated using the following equations (Hairiah *et al*., 2001):

$$\text{Total dry weight} = \frac{\text{Total fresh weight (kg)} \times \text{subsample dry weight (kg)}}{\text{Subsample fresh weight (kg)} \times \text{sample area (m}^2\text{)}} \quad [3]$$

Similarly, the organic matter content of the sample was derived from the following relationship:

$$\%OM = \frac{(\text{Sample} + \text{Crucible Wt}) - (\text{Sample after ash} + \text{Crucible Wt.})}{\text{Sample} + \text{Crucible Wt.}} X100 \quad [4]$$

$$\%OC = \frac{\%OM}{1.742} \quad [5]$$

where OM is organic matter, OC is organic carbon, and 1.724 is Van Bemmelen factor in which OC is assumed to make up 58% of OM (Armeein and Gabon, 2008).

The following formula was used to calculate the biomass of the coffee shrub (Mesele *et al*., 2013):

$$Y = b_1 d^2{}_{40} \quad [6]$$

where Y is the biomass, d_{40} is stump diameter at 40 cm height and b_1 is coefficient for the squared power equation for the above formula produced with the cross-validation ‘‘training’’ coffee plants in Ethiopia and whose value is 0.147 (Mesele *et al*., 2013).

The carbon stock of the shade trees in coffee agroforestry was determined using the formula developed by Pearson *et al*. (2005):

$$AGB = 0.2035 * DBH^{23196} \qquad [7]$$

3.2.5. Estimation of soil organic carbon stock

The organic carbon content of soils obtained from laboratory analysis was used to calculate carbon stock per unit area of land. The carbon stock for each layer was calculated as (Pearson *et al*., 2005):

$$C_i = BD_i(1 - CF_i) \times d_i \times OC_i \qquad [8]$$

where C_i is C stock of the ith layer, BD_i is bulk density of the ith layer (kg/m^3), CF_i is coarse fragment content of the ith layer, OC is the soil’s organic C content (%), d_i is thickness of the ith layer (m). Finally, the carbon stock is expressed in tonne (t) ha^{-1} by multiplying the value obtained using Equation 8 by a conversion factor of 10.

Coarse fraction was determined during sample preparation after repeated crushing of clods by hand, mechanical grinding, drying, and sieving until the sample was passed through a 2 mm sieve. Following this, the coarse fraction was weighed and its proportion was determined using the relationship (Zhang *et al.*, 2008):

$$\text{Coarse fraction}(\%) = \left(\frac{\text{Total weight} - \text{weight of fraction} < 2\,\text{mm}}{\text{Total weight}}\right) \times 100 \qquad [9]$$

The total carbon stock for the 0-60 cm depth was calculated as:

$$C_{total}\ (\text{t ha}^{-1}) = \sum_{i=1}^{3} Ci \qquad [10]$$

The dry bulk density was calculated using the following equation:

$$\text{BD (kg/m}^3\text{)} = \frac{M_{ODS}\ (\text{kg})}{V_t\,(\text{m}^3)} \qquad [11]$$

where:

M_{ODS} = mass of the oven-dry soil (kg)

V_t = total volume of the soil core (m^3) calculated from:

$$V_t = \pi r^2 h \quad [12]$$

where r is the internal radius of the cores measured using a caliber (m), h is height of the cores measured using a hand tape (m), and Π is a constant which is equal to 22/7.

The total carbon stock (t ha^{-1}) of each land use of the sub-watershed was obtained from:

$$C_{totalstock} = C_{AG} + C_{BG} + C_{LT} + C_{Soil} \quad [13]$$

where C_{AG} is aboveground carbon, C_{BG} is belowground carbon, C_{LT} is litter carbon, and C_{soil} is soil carbon.

3.2.6. Calculation of deterioration index

Deterioration index (DI) of soils under coffee agroforestry, grazing land, and crop land was computed assuming that the level of organic carbon and total nitrogen contents under these land uses before conversion were once the same with soils under less influenced natural forest. The changes were averaged across the two dynamic soil properties to generate the overall soil deterioration index (Adejuwon and Ekanade, 1988). The following relationship was employed to compute deterioration index for the individual soil properties:

$$\mathrm{DI}\,(\%) = \left[\frac{\mathrm{PSL} - \mathrm{PRL}}{\mathrm{PRL}}\right] \times 100 \quad [14]$$

where, PSL is mean value of individual soil property (P) under specific land use (SL), PRL is mean value of individual soil property (P) under reference land use (RL), and DI is deterioration index.

3.2.7. Statistical analysis

The data were grouped and summarized according to the land uses and soil depths. The standard error of mean was calculated for each parameter and depths of the soil and vegetation. The data for individual depths was also subjected to ANOVA (analysis of variance). Least significant difference (LSD) was used to separate means that are significantly different from each other at P

< 0.05. Besides, statistical differences were tested using two-way analysis of variance (ANOVA) to identify whether differences in soil attributes between the land uses and sampling depths are significant or not following the generalized linear model (GLM) procedure of SPSS Version 20.0 for Windows.

3.3. Characterization of Climate, Soil and Landscape for Land Suitability Evaluation

3.3.1. Data source and collection

The soil and landscape information was generated from own soil survey. A Landsat ETM+ 7 image and Digital Elevation Model (30 x 30 m resolution) were used to delineate preliminary land mapping units. This was supported by a semi-detailed survey using topographic map of 1:50000 scale. Subsequently, based on the free field survey, five land mapping units were identified. Features like land use/land cover, landform, slope, soil color, and texture were used to differentiate the land mapping units. A total of 15 auger pits were observed and five representative pedons were opened on the identified five land mapping units (Figure 3.5). The auger pit observation points and the pedon sites were geo-referenced using Gramin GPS (Figure 3.4). The auger pits and pedons were described as per FAO (2006) guidelines for soil description. Soil samples were collected from the identified genetic horizons, prepared for laboratory analysis, and analyzed for soil properties that are relevant for classification of the soils and undertaking land suitability evaluation. The soil samples were analyzed at Haramaya University Soil Laboratory following standard laboratory procedures developed for each parameter. Classification of the soils was done using the World Reference Base for Soil Resources (WRB) (IUSS Working Group WRB, 2015) and the final soil map was produced using ArcGIS 10.4.1 software. The soil mapping units and their area coverage is depicted in Table 3.2. Since Pedon 5 was opened in the forestland, it was not considered in the land suitability evaluation for crop production. Because the soil mapping units were the same as the land mapping units, we preferred to use Soil Mapping Units in the preparation of suitability maps.

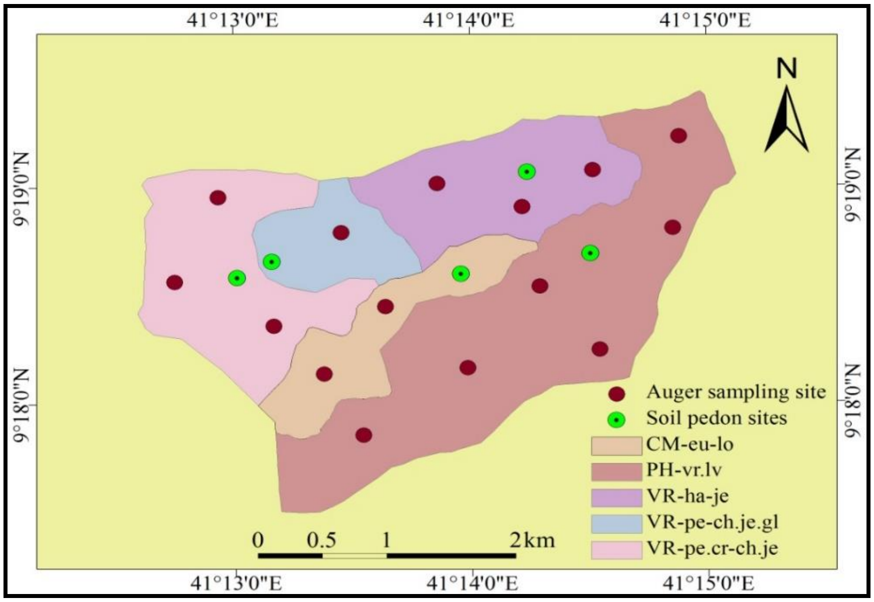


Figure 3.4: Distribution of soil pedon and auger observation points at Hades Sub-watershed.

In general, three Reference Soil Groups, Vertisols, Cambisols and Phaeozems, are identified in the sub-watershed.

Table 3.2: The identified soil mapping units, their area coverage, and soil types at Hades Sub-watershed, eastern Ethiopia

Mapping unit	Slope (%)	Soil depth (cm)	Area ha	Area %	Soil classification
VR-pe.cr-ch.je	7	> 144	201	20.7	Chromic Pellic Vertisols
VR-pe-je.gl	5.5	> 94	79	8.1	Pellic Vertisols
CM-eu-lo	16	> 21	107	11.0	Eutric Cambisols
VR-ha-je	3.5	> 139	166	17.1	Haplic Vertisols
PH-vr.lv	11	124+	418	43.0	Luvic Vertic Phaeozems

3.3.2. Description and characterization of the soil mapping units

Soil mapping unit 1 (VR-pe-cr-ch.je)

This soil mapping unit refers to well-drained soil occurring on level land at toe slope (0-7%) covering an area of nearly 201 ha. It has a texture of sandy clay with moderate fine subangular blocky structure and friable moist consistence, very deep effective soil depth of 144 cm with black (2.5Y2.5/1, moist) and very dark gray (2.5Y3/1, dry) surface soil color. This mapping unit is characterized by neutral soil pH of 6.8, low organic carbon content (1.7%) (Landon, 2014), very high cation exchange capacity of 42.2 cmol (+)/kg (Metson, 1961) and very high base saturation of 92.2% (Metson, 1961) which qualified for chernic surface diagnostic horizon. It is also described by vertic subsurface diagnostic horizon with high clay content and cracking property due to swelling and shrinking upon wetting and drying. Hence, the soil was classified as Vertisols and further qualified for pellic and chromic color properties and described as Chromic Pellic Vertisols (Chernic, Hypereutric). Table 3.3 illustrates the selected soil properties.

Soil mapping unit 2 (VR-pe-ch.je.gl)

This mapping unit represents the imperfectly drained soils occurring on level land at toe slope (0-5.5%) covering 79 Ha. It has a texture of sandy clay with weak fine angular blocky structure and friable moist consistence, deep effective soil depth of greater than 94 cm and had black (10YR2/1, moist) surface soil color. This soil has a pH value of 7.7, very low organic carbon content of 0.84% (Landon, 2014), very high cation exchange capacity of 48.8 cmol (+)/kg (Metson, 1961) and very high base saturation of 100. It is characterized by vertic subsurface horizon with high clay content and cracking due to swelling and shrinking upon wetting and drying. Hence, the soil is classified as Vertisols. The soil was further described by pellic due to having a colour value of 2 and chroma of 1 in the upper 36 cm of the soil and possessed gleyic property resulting from groundwater saturation, thereby qualified for Pellic Vertisols (Hypereutric, Gleyic). The selected soil properties are presented in Table 3.3.

Soil mapping unit 3 (CM-eu-lo)

This mapping unit refers to the excessively well-drained soils occurring on sloping land at the middle slope (16%) covering an area of about 107 ha. It had very dark brown (7.5YR2.5/3, moist) surface soil color and 21 cm depth. This soil is sandy clay loam in texture which met loamic qualifier criteria and was characterized by weak fine angular blocky structure along with the presence of coarse fragments evidenced to pedogenetic alteration of original rock structure (a cambic subsurface diagnostic horizon). Thus, it qualified for Cambisols (Loamic) Reference Soil Group (RSG). The soil has a pH value of 7.57 and characterized by very low organic carbon content (1.64%) (Landon, 2014), moderate cation exchange capacity of 22.6 cmol (+)/kg and very high base saturation of 100 (Metson, 1961). Due to its high base saturation content, this soil was further classified as Eutric Cambisols (Loamic). Selected soil properties of the representative pedons is indicated in Table 3.3.

Soil mapping unit 4 (VR-ha-je)

This mapping unit refers to the imperfectly drained soil occurring on level land at middle lower slope (3.5%) covering 166 ha. It had very dark brown (10YR2/2) moist surface soil color, very deep effective soil depth of greater than 139 cm, sandy clay loam texture with weak medium angular blocky structure and friable moist consistence. The soil pH was 6.9 with very low organic carbon content (1.48%) (Landon, 2014), very high cation exchange capacity of 46 cmol (+)/kg and very high base saturation of 93.06 (Metson, 1961) (Table 3.3). The soil has high clay content characterized by cracking due to swelling and shrinking upon wetting and drying, which qualified for vertic subsurface diagnostic horizon. Therefore, the soil is classified as Vertisols and further described as Haplic Vertisols (Hypereutric) because no more diagnostic horizon or property or material was observed in this pedon.

Soil mapping unit 5 (PH-VR.LU)

Soil mapping unit 5 was opened at back slope (11%) of natural forest and covering 418 ha. The soil characterized by imperfectly drained clay and silty clay textures with moderate medium angular blocky structure in the surface layer and moderate very fine to medium subangular blocky in the subsurface layers. Its consistency was friable when moist throughout the profiles whereas it varied from sticky and plastic in the surface layer and deeper layer (75-124 cm) and slightly plastic in the subsurface layer (43-75 cm). It had black (10YR 2/10) mollic horizon with high organic carbon (1.82%) and high base saturation ($\geq$ 80%) in the entire depth; high shrink-swell clay content in the subsurface layer (vertic and luvic properties). Therefore, it can be categorized under the Luvic Vertic Phaeozem. Table 3.3 shows selected soil properties of the representative pedon.

Table 3.3: Selected physical and chemical soil properties of the pedons representing the soil mapping units

Pedon no. (SMU)	Depth (cm)	OC (%)	CEC ($Cmol_c kg^{-1}$)	Exchangeable bases ($Cmol_c kg^{-1}$) Ca	Mg	Na	K	PBS (%)	ESP	pH	P ($mg kg^{-1}$)	Particle size distribution (%) Sand	Clay	Silt	TC
1 (SMU1)	0-19	1.70	42.2	29.75	7.96	0.50	0.72	92.19	1.12	6.80	8.25	48	38	14	SC
	19-67	1.00	41.0	29.44	8.39	0.70	0.64	95.56	1.71	7.21	1.18	47	43	10	SC
	67-98	0.76	40.4	33.83	9.63	1.00	1.01	100.00	2.42	7.79	1.00	47	43	10	SC
	98-144	0.40	42.6	35.12	10.60	1.30	0.93	100.00	3.00	7.67	2.24	46	45	9	SC
2 (SMU2)	0-36	1.45	48.8	35.19	12.40	1.80	0.54	100.00	3.58	7.70	9.02	48	36	16	SC
	36-71	1.40	47.2	36.67	11.70	1.50	0.41	100.00	3.11	7.72	12.60	47	38	15	SC
	71-94	0.48	57.8	36.23	13.00	1.50	0.70	88.96	2.63	7.64	8.43	46	39	15	SC
3 (SMU3)	0-21	1.64	22.6	22.53	3.27	0.40	1.99	100.00	1.63	7.57	10.30	67	20	13	SCL
	21-48	0.65	43.2	29.44	5.09	0.50	1.86	85.34	1.09	6.96	2.65	58	30	12	SCL
	48-101	0.59	43.8	35.56	4.66	0.70	1.55	96.91	1.56	7.21	3.94	56	26	18	SCL
4 (SMU4)	0-19	1.48	46.0	34.14	7.54	0.50	0.62	93.06	1.10	6.90	14.90	49	34	17	SCL
	19-96	1.38	42.4	33.89	10.70	0.80	0.62	100.00	1.90	7.40	23.60	48	34	18	SCL
	96-139	0.59	40.4	28.15	9.71	0.80	2.60	102.02	1.86	7.76	0.41	49	44	7	SC

SMU = Soil Mapping Unit; OC = Organic carbon; PBS = Percent base saturation; ESP = Exchangeable sodium percentage; TC = textural class

3.3.3. Agro-climatic analysis

All the climatic data, pertinent to the suitability evaluation, was obtained from Ethiopian Meteorological Service Agency. The climatic characteristics on which data were obtained include rainfall, maximum and minimum temperatures, wind speed, relative humidity, and duration of sunshine hours. These climatic characteristics were used for preliminary determination of the length of growing period, planting date, the crop variety, and climatic suitability evaluation.

The monthly data of rainfall were changed to decadal values using the FAO CROPWAT 8 Windows Version. Reference evapotranspiration was computed from the above-listed climatic parameters using the same model, which uses the Penman-Monteith method for calculating reference crop evapotranspiration.

Both graphic and linear interpolation methods were used for the determination of the start of the growing period, the start and end of humid period, end of rains, and end of the growing period. The end of growing period was determined using the simple water balance calculation to consider the assumed 100 mm soil water storage after the end of rain (FAO, 1983; Sys *et al*., 1991a, b).

The linear interpolation method uses the following algorithm to determine the time that corresponds to the beginning of the growing period or end of the rains (Sys *et al*., 1991a):

$$\text{If} \begin{Bmatrix} R_1 < \frac{E_1}{2} \text{ and } R_2 > \frac{E_2}{2} \\ \text{or} \\ R_1 > \frac{E_1}{2} \text{ and } R_2 < \frac{E_2}{2} \end{Bmatrix} \text{then } t = \text{int eger } \frac{\left[\left(R_1 - \frac{E_1}{2}\right) \times 30\right]}{\left[(R_1 - R_2) + \left(\frac{E_2}{2} - \frac{E_1}{2}\right)\right]} \qquad [15]$$

where R_1 and R_2 are rainfall in the two successive decades, E_1 and E_2 are reference evapotranspiration in the two successive decades and t is the time in days starting from the middle of the first decade.

The start and end of humid period were determined the following algorithm (Sys *et al*, 1991a)

$$\text{If } \begin{cases} R_1 < E_1 \text{ and } R_2 > E_2 \\ \text{Or} \\ R_1 > E_1 \text{ and } R_2 < E_2 \end{cases}, \text{ then } t = \text{Integer} \frac{[(R_1 - E_1) \times 30]}{[(R_1 - R_2) + (E_2 - E_1)]} \qquad [16]$$

3.3.4. Selection and description of the land utilization types

The description of the land utilization types, which involves quantification of produce, management types, and set of land use requirements, was done following the procedures described by Sys *et al*. (1991a) and FAO (1983). The study area is characterized by low level subsistence farming with low market orientation, small (less than 1 ha) and fragmented land holdings, traditional physical soil conservation works and labor-intensive types of rainfed crop production system, with oxen serving as the major source of traction for plowing. For this study, five land utilization types were identified in consultation with local community and agricultural development agents, and importance of the crops in the area. The identified land utilization types were sorghum (*Sorghum bicolor* L.), maize (*Zea mays* L.), coffee (*Coffea Arabica*), finger millet *(Eleusine coracana* L) and upland rice (*Oryza sativa*).

FAO (1984) grouped physiological maturity of sorghum into early maturing (< 180 days), medium maturing (150/180-210 days), and late-maturing (180 – 240 days). Sorghum varieties currently cultivated at the sub-watershed (Birhan/PSL85061 and Hornat/IESVIII2BF) are within the medium maturing category. Similarly, FAO (1984) categorized maize into maturity groups of early maturing (60-120 days), medium maturing (150-180 days), and late maturing (180-210 days). Accordingly, maize varieties currently cultivated at Hades Sub-watershed (BH-160, BH-161, BH-543, and BH-140/BHQPY-545) belong to the medium maturing category. Upland rice variety selected for evaluation was Superica-1, which is new to the study area and has 120 days cycle. Finger millet with 120 – 150 days was also considered for suitability evaluation.

Hades Sub-watershed is characterized by bimodal rainfall that ranges from 600-900 mm (MOA, 2005). For the late-maturing sorghum varieties, which have a crop cycle of 180-240 days and optimum temperature requirement of 17.5-22.5 °C, 3150-5400 degree days are required to reach maturity. Under the low mean temperature of the growing period in the study area, the required degree days are achieved within 215-369 days. Because this is within the 239 length of growing period in the study area, this late-maturing sorghum variety was considered for further evaluation. By similar analogy, the late-maturing maize varieties (180-210 days), finger millet (120 – 150), and upland rice (120 days) were considered for further evaluation. A perennial crop, coffee, was also considered in consultation with farmers and agricultural development workers.

3.3.5. Determination of land use requirements

Following the procedure of FAO (1976, 1983), FAO (1984), and Sys *et al.* (1991, 1993), the LURs for the selected LUTs were established through a review of experimental research findings and literatures on parameters such as length of the growth period and time to maturity, specific environmental and soil physical and chemical requirements and adaptation of the already established requirements of these crops under Ethiopian agro-ecological conditions. The reviews were consolidated through consultation with local agronomists, soil experts, and experts working in related disciplines. The land use requirements of the late-maturing sorghum and maize varieties, finger millet, coffee, and upland rice are presented in Tables 3.5 - 3.9, respectively.

3.3.6. Selection of land qualities, characteristics, and diagnostic criteria for suitability evaluation

The suitability evaluation for the crops was determined based on the collection and characterization of data on relevant land characteristics and/or qualities, description of the LUTs, determination of the requirements of the LUTs, evaluation *sensu stricto* by comparing the land characteristics and/or qualities with the requirements of the LUTs using the procedures outlined in FAO (1976, 1983, 2007) and Sys *et al*. (1991a).

Land use requirements with their diagnostic criteria included: temperature regime (mean temperature) during growing season (°C), moisture availability (mean annual rainfall and rainfall in growing season), length of growing period (days), nutrient availability (pH, P, organic matter, and basic cations), nutrient retention capacity (cation exchange capacity), rooting conditions (soil effective depth), physical characteristics, slope, and drainage conditions. Each criteria of the land quality was rated as highly suitable (S1), moderately suitable (S2), marginally suitable (S3) and not suitable (N) based on the level of land quality required by each LUT (Tables 3.5-3.9). The selected soil and landscape characteristics are presented in Table 3.4.

Table 3.4: Soil and landscape characteristics used for suitability evaluation of rainfed production of sorghum, maize, coffee, finger millet and upland rice at Hades Sub-watershed, eastern Ethiopia

Soil and landscape characteristics	Soil mapping units			
	*SMU 1	SMU 2	SMU 3	SMU 4
Slope (%)	7	5.5	16	3.5
Effective depth (cm)	144	94	101	139
Drainage	Imperfectly drained	Imperfectly drained	Excessively well drained	Imperfectly drained
Flooding	No flooding	No flooding	No flooding	No flooding
Texture	Sandy Clay	Sandy Clay	Sandy Clay Loam	Sandy Clay
Coarse fragment (%)	1.0	0.58	10.0	9.3
Soil reaction (pH-H_2O)	6.99	7.70	7.47	7.02
Apparent CEC (cmol(+) kg^{-1} clay)	95.3	124.2	113.0	124.7
Sum of basic cations (cmol (+) kg^{-1} soil	38.44	48.12	29.17	43.00
Organic carbon (%)	1.53	1.45	1.44	1.46
Available Phosphorous (mg kg^{-1})	6.55	9.02	9.08	16.99

*SMU = Soil Mapping Unit

3.3.7. Physical land suitability evaluation (matching)

The maximum limitation method was used for determination of the land suitability classes of the land units (FAO, 1983; Sys *et al.*, 1991a, b). Climatic attributes were evaluated separately based on the maximum limitation method resulting in agro-climatic suitability class and the soil and landscape attributes were evaluated based on the same method resulting in soil and landscape suitability. The overall suitability classes and sub-classes were obtained by combining the agro-climatic suitability with the soil and landscape suitability, according to the maximum limitation method. The evaluation *sensu stricto* was realized by comparing the land characteristics with the land use requirements of the specified land utilization types.

3.3.8. Land suitability mapping

The geographic information system software GIS version 10.4.1 was used for the production of the suitability maps of the land units for the identified land utilization types.

Table 3.5: Crop environmental requirement for late-maturing grain sorghum (180-240 days) production

Land use requirements			Factor rating			
Land qualities	Diagnostic factor	Unit	S1	S2	S3	N
Temperature regime	Mean temperature in growing period	^{o}C	17.5-22.5	15.0-17.5 22.5-25.0	13.0-15.0 25.0-32.0	<13 >30.0
Moisture availability	Length of growing period	days	180-240	150-180 240-270	90-150 270-310	<90 >310
	Total rainfall during growing period	mm	400-900	300-400 900-1200	150-300 1200-1400	<150 >1400
Oxygen availability	Soil drainage class	Class	MW,W,S, E	I	P	V
Nutrient availability	Soil reaction	pH-H_2O	5.5-8.2	5.5-5.3 8.2-8.3	5.3-5.0 8.3-8.5	<5.0 >8.5
	Organic matter	%	>3	2-3	1-2	0-1
	Available P	mgkg^{-1}	10+	5-10	3-5	<3
	Apparent CEC	cmol(+) kg^{-1} clay	13->25	6-13	3-6	<3
	Sum of basic cations	cmol(+) kg^{-1} soil	10->15	7.5-10	<7.5	-
Rooting condition	Effective soil depth	cm	>100	50-100	25-50	<25
Soil workability	Coarse fragment	%vol.	0-15	15-35	35-55	>55
	Soil texture/structure	Class	L,CL,Si,SiC L,SiL,SCL	SL	LS,S	Cm,SiCm,S
Erosion hazard	Slope	%	0-8	8-16	16-30	>30
Flood hazard	Flood frequency	Class	F0	-	F1	F1,F2,F3

Note: W = well drained, MW = moderately well drained, I = imperfect drained, P = poorly drained, VP = very poorly drained, L=loam, CL = clay loam, Si = silt, SiCL=silty clay loam, SC = sandy clay, SL = sandy loam, LS = loamy sand, Cm = massive clay, S = sand, Fo = no risk, F1 = slight, F2 = common, F3 = frequent, F4 = permanent, Source: Adapted from FAO, (1983), FAO (1984, 1987), Sys *et al*. (1991,a,b,c), Mohamed (2004), Dawit, (2010),

Table 3.6: Crop environmental requirement for late-maturing grain maize (180-210 days) production under rainfed conditions

<table>
<tr><th colspan="3">Land use requirements</th><th colspan="4">Factor rating</th></tr>
<tr><th>Land qualities</th><th>Diagnostic factor</th><th>Unit</th><th>S1</th><th>S2</th><th>S3</th><th>N</th></tr>
<tr><td>Temperature regime</td><td>Mean temperature in growing period</td><td>^{o}C</td><td>17.5-22.5</td><td>15.0-17.5
22.5-25.0</td><td>13.0-15.0
25.0-32.0</td><td><13
>30</td></tr>
<tr><td rowspan="2">Moisture availability</td><td>Length of growing period</td><td>days</td><td>180- 210</td><td>150-180
210-270</td><td>90-120
270-310</td><td>-</td></tr>
<tr><td>Total rainfall during growing period</td><td>mm</td><td>300-1100</td><td>300-200
1100-1300</td><td>200-150
1300-1500</td><td><120
>310</td></tr>
<tr><td>Oxygen availability</td><td>Soil drainage class</td><td>Class</td><td>MW,W,S, E</td><td>-</td><td>I</td><td>P,VP</td></tr>
<tr><td rowspan="3">Nutrient availability</td><td>Soil reaction</td><td>$pH\text{-}H_2O$</td><td>6.0-7.0</td><td>5.2-6.0
7.0-7.5</td><td>5.0-5.2
7.8-8.</td><td><5.0
>8.0</td></tr>
<tr><td>Organic matter</td><td>%</td><td>>3</td><td>2-3</td><td>1-2</td><td>0-1</td></tr>
<tr><td>Available P</td><td>$mgkg^{-1}$</td><td>10+</td><td>5-10</td><td>3-5</td><td><3</td></tr>
<tr><td rowspan="2">Nutrient retention capacity</td><td>Apparent CEC</td><td>cmol(+) kg^{-1} clay</td><td>16-24</td><td colspan="2"><16</td><td>-</td></tr>
<tr><td>Sum of basic cations</td><td>cmol(+) kg^{-1} soil</td><td>3.5 - >5</td><td>3.5-2</td><td>3.5-<2</td><td>-</td></tr>
<tr><td>Rooting condition</td><td>Effective soil depth</td><td>cm</td><td>>100</td><td>50-100</td><td>25-50</td><td><25</td></tr>
<tr><td>Soil workability</td><td>Soil texture/structure</td><td>Class</td><td>L,CL,Si,SiC
L,SiL,SCL</td><td>SiC,C,SC,S
L</td><td>LS, Cm</td><td>S</td></tr>
<tr><td>Flood hazard</td><td>Frequency</td><td>Class</td><td>Fo</td><td>F1</td><td>F2</td><td>F4</td></tr>
<tr><td>Erosion hazard</td><td>Slope</td><td>%</td><td>0-8</td><td>8-16</td><td>16-30</td><td>>30</td></tr>
<tr><td>Flood hazard</td><td>Flood frequency</td><td>Class</td><td>F0</td><td>-</td><td>F1</td><td>F1,F2,F3</td></tr>
</table>

Note: W = well drained, MW = moderately well drained, I = imperfect drained, P = poorly drained, VP = very poorly drained, L=loam, CL = clay loam, Si = silt, SiCL=silty clay loam, SCL = sandy clay loam, SC = sandy clay, SL = sandy loam, LS = loamy sand, Cm = massive clay, S = sand, Fo = no risk, F1 = slight, F2 = common, F3 = frequent, F4 = permanent,

Source: Adapted from FAO (1983), FAO (1984, 1987), Sys *et al*. (1991,a,b,c), Mohamed (2004)

Table 3.7: Land use requirements of finger millet (120-150 days) production

Land use requirements			Factor rating			
Land qualities	Diagnostic factor	Unit	S1	S2	S3	N
Temperature regime	Mean temperature in growing period	ºC	24-22, 24-26	20-18, 28-30	18-16, 30-32	> 36, < 16
Moisture availability	Length of growing period	days	> 150	90 - 150	75 - 90	< 60
	Total rainfall during growing period	mm	>900	600-900	450 - 600	< 450
Oxygen availability	Soil drainage class	Class	Good, Imperfect	Imperf, Good	Poor, aeric	Poor, Not drainable
Nutrient availability	Soil reaction	pH (H201: 2.5)	5.5- 7.5	4.5 - 5.5; 7.6 - 8.5	4.0 - 4.4 ; 8.6 - 9.5	<4.4; <9.5
	Organic matter	%	>2.8	2.8 - 2.0	2.0 - 0.8	<0.8
	Available P	ppm	>14	14-5	5 -2.	< 2
	Apparent CEC	cmol(+) kg^{-1} clay	>30	30 – 20	20 – 10	<10
	Sum of basic cations	(cmol(+)/kg soil)	>25	25 – 15	15 – 3	<3
Soil workability	Soil texture/structure	class	L,SiL, SL,SiC,L,S CL	SiC, C, SC, CL	LS, S, C>60%	
Erosion hazard	Slope	%	<3	3 - 5.	5 - 10	> 10
Flood hazard	Flood frequency		F0	F1	F3	F3+

Note: L=loam, CL = clay loam, SiL = silt loam, , SC= sandy clay, L=loam, CL=clay loam, LS = loam sandy, SiC = silt clay, C = clay, S = sandy, C . 60% = heavy clay Fo = no risk, F1 = slight, F2 = common, F3 = frequent,
Source: FAO, 1984; Sys *et al*., 1993; Naidu *et al*., 2006

Table 3.8: Crop environmental requirement for coffee production under rainfed conditions

Land use requirements			Factor rating			
Land qualities	Diagnostic factor	Unit	S1	S2	S3	N
Temperature regime	Mean temperature in growing period	^{o}C	19-18 19-20	16-15 22-24	15-14 24-26	< 14 >26
Moisture availability	Length of growing period	days				
	Total rainfall during growing period	mm	1500-1600 1500-1400	1800-2000 1200-1000	> 2000 1000-800	< 800
Oxygen availability	Soil drainage class	Class	Good	Good	Moderate	Poor not drainable
Nutrient availability	Soil reaction	pH-H_2O	6.0-5.8 6.0-6.2	5.6-5.4 6.6-7.4	5.4-5.2 7.4-7.8	< 1.6 < 5.2
	Organic matter	%	> 2.4	1.2-0.8	< 0.8	> 7.8
	Available P	$mgkg^{-1}$				
	Apparent CEC	cmol(+) kg^{-1} clay	> 24	< 16(-)	< 16(+)	-
	Sum of basic cations	cmol(+) kg^{-1} soil	> 6.5	4-2.8	.8-1.6	< 1.6
Rooting condition	Effective soil depth	cm	> 200	150-100	100-50	< 50
Soil workability	Course fragment	%vol.	0-3 3-15	15-35	35-55	> 55
	Soil texture/structure	Class	C<60s,Co, SiCL,CL	SCL	SL,LfS	Cm,SiCm C>60v, LS,LcS, cS,fS
Erosion hazard	Slope	%	0-1	2-4	4-6	> 6
Flood hazard	Flood frequency	Class	Fo	Fo	Fo	F1+

Source: Adapted from FAO (1983), FAO (1984, 1987), Sys *et al*. (1991,a,b,c), Mohamed (2004)

Table 3.9: Crop environmental requirement for upland rice (120 days cycle) production under rainfed conditions

Land use requirements			Factor rating			
Land qualities	Diagnostic factor	Unit	S1	S2	S3	N
Temperature regime	Mean temperature in growing period	°C	31-30 31-32	24-18 > 36	18-10	< 10
Moisture availability	Length of growing period	days				
	Total rainfall during growing period	mm	200-300 200 - 75	400-550	550-650	> 650 < 50
Oxygen availability	Soil drainage class	Class	Good	Imperfect	Poor, aeric	Poor not drainable
Nutrient availability	Soil reaction	pH-H_2O	6.5-6.0 6.5-7.0	5.5-5.0 7.5-7.9	5.0-4.5 7.9-8.2	< 4.5
	Organic matter	%	> 2	1.5-0.8	< 0.8	
	Available P	$mgkg^{-1}$				
	Apparent CEC	cmol(+) kg^{-1} clay	> 24	< 16(-)	< 16(+)	
	Sum of basic cations	cmol(+) kg^{-1} soil	> 4	2.8-1.6	< 1.6	
Rooting condition	Effective soil depth	cm	> 120	90-50	50-20	< 20
Soil workability	Course fragment	%vol.	< 3 3 - 15	15-35	35-55	> 55
	Soil texture/structure	Class	SiCs,Co, SiCL,Cl, Si,SiL	C+60v, SCL,SL, LfS	LS,LcS, fS	S,cS
Erosion hazard	Slope	%	0-2 0-4	4-8 8-16	8-16 16-30	> 25 > 30
Flood hazard	Flood frequency	Class	no	Fll	F12-F13	> F13

Source: Adapted from FAO (1983), FAO (1984, 1987), Sys *et al*. (1991,a,b,c), Mohamed (2004)

3.4. Biomass Projection and Carbon Sequestration Potential

3.4.1. Climate data

Two types of climate data were employed in this study. The first one is observed long term daily climate data, from 1980 – 2014, which was obtained from National Meteorological Agency (NMA) of Ethiopia. The climate data (1980 - 2014) were filled for gaps based on standard procedures. The second set of data used was daily rainfall and monthly minimum and maximum temperatures projected for near-term (2010 - 2039) and mid-term (2040 - 2069) periods.

The future rainfall and minimum and maximum temperatures were taken from the outputs of several Global Circulation Models (GCMs) made by The Coupled Model Intercomparison Project Phase 5 (CMIP5). The resolution of the GCMs ranges from 41°13’0 - 41°15’0 E and 9°18’0 - 9°19’0 N. Future projections of the monthly minimum and maximum temperatures for the two time slices and grid box containing the study area were downloaded from the Climate Explorer website (www.climexp.knmi.nl).

As a good practice, the user’s manual for the AquaCrop model recommends the use of daily data for rainfall at a reasonably finer resolution. Furthermore, rainfall over the study area would be impacted by the rugged topography, and, hence, the direct use of the GCMs outputs for impact studies would incur erroneous results and may lead to faulty conclusions based on such coarse resolutions. For this reason, bias-corrected Coordinated Downscaling Experiment (CORDEX) downscaled regional climate scenario data of daily rainfall (at a resolution of 0.44 degree grid, which is approximately 50 km spatial resolution at the equator), from the CORDEX initiative, corresponding to the same four GCMs used for temperature scenarios, provided through SMHI was used in this study.

The Coordinated Regional Climate Downscaling Experiment, CORDEX (http://www.cordex.org/, (Giorgi *et al*., 2009; Jones *et al*., 2011), is an internationally coordinated effort sponsored by the World Climate Research Program’s (WCRP) Working Group on Regional Climate. The aim is to provide homogeneously designed regional climate model output for the world’s land areas. In order to use the output from Regional Climate Models (RCMs) for impact studies, post-processing of the raw RCM data (for example temperature and rainfall) is required. This is because the RCM results contain systematic errors (bias) that reduce their applicability for impact studies. The CORDEX (Giorgi *et al*., 2009; Jones *et al*., 2011) climate scenario data were bias corrected at the Rossby Centre, SMHI, Sweden for mean temperature and rainfall using the Distribution Based Scaling method (DBS) (Yang *et al*., 2010) and WATCH-Forcing-Data-ERA-Interim (WFDEI) (Weedon *et al*., 2014) as reference dataset.

The Reference evapotranspiration (ETo) is among the set of required input climatic parameters for the AquaCrop model. For the validation phase, ETo was estimated using the ETo Calculator, based on observed daily minimum and maximum temperatures, relative humidity, solar radiation, and wind speed data. For each of the Multi Model Ensemble (MME) and the two future time periods, ETo was estimated based on future projections of daily minimum and maximum temperatures. The average atmospheric CO_2 concentration (369.41 ppm by volume) measured for the year 2000 at Mauna Loa Observatory in Hawai (Malamud *et al*., 2011) was used as a reference default value.

The daily observed baseline climate data was used as an input for the AquaCrop model to simulate the biomass development of maize and sorghum under past and current climate conditions. Several years of yield data of the two crops collected by Zonal agriculture offices were used for calibration and validation of the model. Similarly, future projected climate data (temperature and rainfall) were used as inputs to the AquaCrop model for simulating future extent of biomass development and grain yield of the two crops in the study area.

3.4.2. Selection of climate scenarios (RCPs)

Two climate scenarios, RCP4.5 and RCP8.5, were selected for this study. The basis for selection of the two RCPs was their likely impact on CO_2 emission to the atmosphere and biomass production for sequestration of carbon under different management practices. Thus, with the selected models and emission scenarios present in the CORDEX-GCM Africa Group, future climate change (temperature and rainfall) were analyzed for two time slots centered in 2030 (2010-2049) and 2050 (2040-2069) and were compared with the baseline period (1981-2009).

3.4.3. Agronomic and management input data for AquaCrop model

As indicated by Hsiao *et al*. (2012), AquaCrop model requires plant, soil, and management related parameters for running the simulation. Those plant related parameters fall under two groups. The first group pertains to those parameters affected by planting and management (planting method, planting density, seed rate and time to reach 90% seedling emergence), while the second group relates to cultivar specific parameters (time to reach maximum canopy cover, to beginning of canopy senescence, time to start flowering and days to maturity). Maximum effective rooting depth is the parameter related to soil characteristics. Management related parameters include rate of fertilizer application, chemical material, and method and time of application of the fertilizers. Table 3.10 contains detailed description of the input parameters for the model.

3.4.4. Description of AquaCrop model

The impact of climate change on the crops biomass production was investigated using a dynamic crop model-AquaCrop v.6. AquaCrop is water driven model developed by FAO (Raes *et al*., 2009). The model was used by large number of users for a number of crops under wider range of growing conditions (Steduto *et al*., 2007; Heng *et al*., 2009; Hsiao *et al*., 2009, Pereira *et al*., 2015a; Wu *et al*., 2015; Zhao *et al*., 2015, Tsakmakis *et al*., 2019).

Table 3.10: Crop parameters used for simulating biomass yield using AquaCrop model

Criteria	Sorghum (Muyira-1)	Maize (BH661)
1. Parameters affected by planting and management		
1.1. Planting method	Row sowing	Row sowing
1.2. Planting density	66,666	44,444/ha
1.3. Seed rate	8-10kg/ha	25 kg/ha
1.4. Time to reach 90% seedling emergence	6 days	8-9 days
2. Cultivar specific crop parameter		
2.1. Time to reach maximum canopy cover	35 days	60-70 days
2.2. Time to beginning of canopy senescence	190	150 days
2.3. Time to start flowering	110-120 days	80 days
2.5. Days to maturity	200-210	196 days
3. Parameters affected by conditions in the soil profile		
3.1. The maximum rooting depth (cm)	200	75+

Source: Doba District Agricultural and Rural Development Office (2015)

The model can be applied in various environments by using limited and most easily determined input parameters. The input parameters were stored in the climate, soil, crop and management files of the model where the data can be updated for a specific crop, location and climatic conditions. AquaCrop calculates biomass based on the concepts of normalized water productivity (Steduto *et al*., 2007; Raes *et al*., 2009). The aboveground biomass produced is proportional to the cumulative amount of crop transpiration (ΣTr). Transpiration is correlated with canopy cover, which is proportional to the degree of soil cover. The proportionality factor is the biomass water productivity (WP). AquaCrop WP is normalized for the effect of the climatic conditions which makes the normalized biomass water productivity (WP*) valid for diverse locations, seasons, and CO_2 concentrations (Foster *et al*, 2017). The cumulative aboveground biomass produced was computed using the following equation:

$$B = WP^* \sum_{i=1}^{n} \left(\frac{Tr_i}{ETo_i} \right) \qquad [17]$$

where B = cumulative aboveground biomass produced (kg m^{-3}); WP* = crop water productivity (biomass per unit of cumulative transpiration); Tr_i = daily crop transpiration (mm); ETo_i = daily reference evapotranspiration (mm); n = sequential days spanning the period when B is produced,

Soil data (soil layer, saturated soil water content, soil pH, bulk density and soil organic matter), daily climate data (solar radiation, rainfall, maximum and minimum air temperatures) and other crop management information were entered into a validated model (Steduto *et al*., 2009; Vahid *et al*., 2014; Vanuytrecht *et al.*, 2014). Because of absence of time sequential biomass data, model performance test was done using yield data obtained from Doba district Agricultural Rural Development Office. After confirmation of the satisfactory performance of the model for the target crops, the model was used for assessing the impacts of climate change on the biomass production of both crops.

3.4.5. Model calibration and validation

The model has been parameterized and tested for many crops (Farahani *et al*., 2009; Alishiri *et al*., 2014; Msongaleli *et al*., 2014; Junzeng *et al*., 2019), with various studies showing that the model is capable of simulating canopy cover (CC), biomass development and grain yield of different crops, and their respective cultivars, grown under varying conditions (van Gaelen *et al*., 2015). This leads to the establishment of crop-specific conservative parameters (Hsiao, 2009).

Thus, in this study, while retaining the crop-specific conservative parameters, the AquaCrop model was calibrated for maize (BH661 cultivar) and sorghum (Muyra-1 cultivar) (Table 3.11).

Table 3.11: Yield data used for statistical evaluation of AquaCrop model calibration and validation for maize (BH661) and sorghum (Muyira-1)

Calibration and validation	Year	Yield (t ha^{-1})			
		Maize		Sorghum	
		OBS	SIM	OBS	SIM
Yield data used for model calibration	2012	1.45	1.32	1.00	1.28
	2013	1.55	1.54	1.52	1.31
	2014	1.62	1.62	1.31	1.24
Yield data used for model validation	2015	1.75	1.70	1.16	1.15
	2016	1.28	1.21	1.29	1.27
	2017	1.95	1.86	1.30	1.29
	2018	1.46	1.42	1.42	1.19

Source: Observed (OBS) data obtained from Doba Woreda Agricultur and Rural Development Office and west Haraghe Zone Agricultural Development Office. SIM= Simulated

Due to lack of measured biomass experimental data, the model was calibrated and validated for grain yields using minimum data input calibration procedure (Hadebe *et al.*, 2017). Accordingly, the model was calibrated using independent yield data set for the years 2012 - 2014 and validated for the years 2015 - 2018 (Table 3.11).

Model performance was evaluated using the following statistical parameters: Nash-Sutcliffe efficiency index (E), mean absolute error (MAE), root mean square error normalized (RMSEN) and Willmott's index (d). The Willmott's index (d) provides a single index of model performance that encompasses bias and variability. The closer the index value is to unity, the better the agreement between the two variables that are being compared and vice versa (Willmott *et al.*, 1985 cited by Msongaleli *et al.*, 2014), while RMSEN and MAE were used to evaluate the model prediction errors. The RMSEN, MAE, d and E were computed according to (Moriasi *et al.*, 2007; Hsiao *et al.*, 2009; Paredes *et al.*, 2014; Pereira *et al.*, 2015b):

$$\mathrm{RMSEN} = \frac{1}{O}\sqrt{\frac{\sum (S_i - O_i)^2}{N}} \times 100 \quad [17]$$

$$\mathrm{MAE} = \sqrt{\sum_{i=1}^{N} \frac{(S_i - O_i)}{N}} \quad [18]$$

$$E = 1 - \frac{\sum_{i=1}^{N} (O_i - E_i)}{\sum_{i=1}^{N} (O_i - \overline{O})^2} \qquad [19]$$

The d-index was calculated as (Willmott *et al*., 1985):

$$d = 1 - \frac{\sum (S_i - O_i)^2}{\sum \left(\left| S_i - \overline{O} \right| + \left| O_i - \overline{O} \right| \right)^2} \qquad [20]$$

where S_i is simulated yield value and O_i is observed yield values, $\overline{O}$ is the average value of O_i, Ei is simulated value and N represents the number of observations. When E and d get closer to unity, and RMSEN and MAE approach to zero, they represent positive indicators of model performance. The simulation is considered excellent if RMSEN is less than 10%; it is good if it comes between 10 and 20%; reasonable when it comes between 20 and 30%; and poor when it is greater than 30% (FAO, 2012). The coefficient of efficiency (E) shows how much the overall deviation between observed and simulated values depart from the overall deviation between observed values (O_i) and their mean value ($\overline{O}$). The value of E can range from negative infinity (–∞) to +1, and the model estimation efficiency increases as E gets closer to +1.

3.4.6. Organic carbon and CO_2 equivalent estimation

The carbon stock was derived from the projected biomass using the following formula:

$$C_{stock} = \frac{Biomass}{1.78} \qquad [21]$$

Then after CO_2 equivalent (e) was calculate by multiplying carbon stock by a conversion factor 44/12 (ratio of molecular weight of CO_2 to carbon) as follows:

$$CO_2e = \frac{C_{stock} \times 44}{12} \qquad [22]$$

After predicting rainfall and temperature for the coming 50 years and identifying production limiting constraints, selected adaptation measures were evaluated for their effect on biomass production of late-maturing maize and sorghum varieties under future climate. These adaptations include adjusting sowing dates and irrigation applications. This selection of adaptation measures was based on the assumption that climate change may result in an increase or decrease in the length of growing season relative to the historical period. This change in length of growing period, in turn, affects availability of moisture during different stages of the crops' growth cycles. For instance, early cessation of the rain may induce terminal moisture deficit stress which results in significant yield loss. Supplementary irrigation can offset such losses.

The effects of the adaptation measures were investigated using two planting windows defined by the FAO crop calendar for various locations and agro-ecological zones. These were early planting date (PD_0-15 days-PDo-15D), late planting date (PD_0+15 days), and late planting with supplementary irrigation (PDo+15days+Irr-PDo+15D+Irr). The planting dates were selected against the reference planting date determined based on rainfall criteria in the business as usual (BAU) climate scenario projections. Furthermore, the PD_o was determined based on the projected rainfall scenario and the requirement that the cumulative rainfall since the onset of rainfall should be at least 40 mm. The adaptation measures were evaluated under the two RCPs, four models, and two time slices considered in this study. The reference sowing date and the corresponding early and late planting dates for the different climate models under the two RCPs (4.5 and 4.8) are depicted in Table 3.12.

Irrigation application (PD_0+ 15D + Irr) comprised of a fixed irrigation depth of 30 mm to be applied whenever the root zone allowable depletion is at 40% of plant readily available water (RAW). Whenever the fraction of RAW is at 0% depletion, it indicates that the soil water is at field capacity or no root zone depletion, while 100% RAW depletion indicates that all the readily available water is consumed, indicating that the threshold for stomatal closure is reached. These adaptation measures were evaluated using AquaCrop v6.1. All other management practices such as fertilizers were put under the 'no stress' option of the model, which indicates that plant nutrient availability and other resources, other than water, will not affect biomass production.

Table 3.12: Early and late planting dates with fixed interval of 15 days against the reference planting date used as adaptation measures for projection of biomass yield of sorghum and maize

GCM/ RCM	RCPs	Planting dates		
		PD_0	PD_0-15	PD_0+15
CNRM_CERFACS_CNRM_CM5	RCP 4.5	March 22	March 7	April 6
	RCP 8.5	April 4	March 20	April 19
ICHEC-EC-Earth	RCP 4.5	April 8	March 25	April 23
	RCP 8.5	March 10	February 23	March 25
HadGem2_ES	RCP 4.5	May 9	May 4	June 3
	RCP 8.5	May 13	April 26	May 28
MPI_M_MPI_ESM_LR	RCP 4.5	May 11	April 26	May 26
	RCP 8.5	May 29	May 15	June 13

CHAPTER FOUR

RESULTS

4.1. Carbon Stock under Major Land Use/Land Cover Types of Hades Sub-Watershed, Eastern Ethiopia

4.1.1. Selected soil properties

4.1.1.1. Soil physical properties

The measured soil physical properties indicated significant ($p < 0.05$) differences in bulk density by land uses and soil depths (Table 4.1). However, the interaction effect of land use by soil depth on bulk density was not significant ($p \geq 0.05$) (Table 4.1). Across the three soil depths, significantly lower bulk density values were recorded in soils under the natural forest, whilst higher values were observed in soils under the cropland (Table 4.2). The other two land uses had intermediate values. Except in soils of the coffee agroforestry land use type, bulk density values increased down the soil depth.

Table 4.1: Two way analysis of variance for bulk density (g/cm^3), sand (%), clay (%) and silt (%) under different land uses, soil depth and interaction effect in Hades Sub-watershed

Source of variation	df	BD		Sand		Clay		Silt	
		MS	Sig.	MS	Sig.	MS	Sig.	MS	Sig.
Depth	2	5.68	0.002*	25.76	0.64	178.67	0.06	77.15	0.081
Land use	3	26.79	0.000*	349.68	0.002*	835.49	0.00*	190.57	0.001*
Depth * Land use	6	0.89	0.339	75.08	0.27	16.24	0.94	26.47	0.487

*The mean difference is significant at the 0.05 level.

Sand, silt, and clay content, on the other hand, were significantly ($p<0.05$) affected by land use alone (Table 4.2). Accordingly, significantly higher sand content was measured in soils of the natural forest across the three depths. On the contrary, significantly higher clay content was recorded at the 0-20 cm soil depth of the cultivated and grazing lands (Table 4.2). Except in soils of the natural forest where it decreased, sand content did not show any consistent trend with soil depth in the other land use types. Silt content, on the other hand, exhibited a downward trend with soil depth in soils of the cultivated and grazing lands, showing no consistent variation with depth in the other land use types. Owing to some downward translocation, the clay content revealed an increasing trend with soil depth in all land uses but the grazing land, where it followed no consistent pattern.

Table 4.2: Contents of some selected soil physical properties in relation to different land uses and soil depths (mean ± SD)

Variable	Depth(m)	Land Uses				
		NF	CAF	GL	CR	**Overall**
Bulk Density (g/cm³)	0-20	0.92 (± 0.2)	1.39(± 0.12)	1.13 (± 0.18)	1.42 (± 0.13)	**1.15(±0.31) a**
	20-40	1.09 (± 0.11)	1.36 (± 0.17)	1.24 (± 0.09)	1.49 (± 0.13)	**1.28(±0.21) ab**
	40-60	1.40 (± 0.21)	1.53 (± 0.29)	1.27 (± 0.1)	1.61 (± 0.12)	**1.48(±0.26) b**
	Overall	**1.2(±0.37) a**	**1.43(±0.19) ab**	**1.21(±0.13) ab**	**1.50(±0.13) b**	
Sand (%)	0-20	67.83 (± 7.7)	58.67 (± 3.21)	49.67 ± 2.08	55.67 ± 12.66	**59.93(±9.99)**
	20-40	62.83 (± 2.32)	55.33 (± 7.1)	48 ± 2.1	62.33 ± 13.01	**58.31(±8.64)**
	40-60	59 (± 3.46)	58.33 (± 11.02)	54.33 ± 5.03	49 ± 3.61	**56.13(±8.10)**
	Overall	**63.39(±7.48) b**	**57.44(±6.93) ab**	**50.73(±4.02) a**	**55.67(±10.92) ab**	
Clay (%)	0-20	10.17 (± 2.75)	17 ± 6.1	29 ± 6	29.33 ± 8.1	**19.13(±10.17)**
	20-40	17.5 (± 8.88)	21 ± 7.94	35 ± 5.29	29.33 ± 7.37	**24.07(±10.26)**
	40-60	20.17 (± 2.02)	23 ± 12.49	34 ± 4.58	37 ± 5.29	**26.87(±10.61)**
	Overall	**15.94(±8.53) a**	**20.33(±8.43) a**	**32.67(±5.39) b**	**31.89(±7.18) b**	
Silt (%)	0-20	22 (± 5.29)	24.33 ± 5.03	21.33 ± 4.04	15 ± 5	**20.93(±5.93)**
	20-40	19.67 (± 7.91)	23.67 ± 1.53	16.8 ± 6.84	8.33 ± 7.1	**17.63(±8.26)**
	40-60	40.67 ± 2.89	18.67 ± 2.31	11.67 ± 1.53	14 ± 1.73	**17.00(±3.98)**
	Overall	**20.67(±5.96)b**	**22.22(±3.93)b**	**16.60(±5.82)ab**	**12.44(±5.41)a**	

For each parameter, different letters in a row indicate significant differences between treatment means within one depth ($p < 0.05$). TN = total nitrogen, NF = natural forest, CAF = coffee agroforestry, GL= Grazing land and CR= cropland

4.1.1.2. Soil chemical properties

The two way analysis of variance (Table 4.3) indicates that soil organic carbon and total nitrogen were significantly ($p < 0.05$) affected by soil depth and land uses, while pH was only significantly ($p < 0.05$) affected by land uses. These three soil properties, however, were not significantly affected by the interaction of land uses and depth. On the contrary, C: N was neither affected by land uses nor depth and the interaction of the two.

Table 4.3: Two way analysis of variance for SOC (%), TN (%), C: N and pH (H_2O), under different land uses, soil depths and interaction effect in Hades sub watershed

Source of variation	df	SOC MS	SOC Sig.	TN MS	TN Sig.	C/N MS	C/N Sig.	pH MS	pH Sig.
Depth	2	5.683	0.002*	0.051	0.004*	0.821	0.821	0.017	0.781
Land use	3	26.79	0.000*	0.199	0.000*	7.826	0.151	2.368	0.000*
Depth * Land use	6	0.897	0.339	0.018	0.055	6.756	0.17	0.022	0.921

The mean difference is significant at the 0.05 level.

The pH of the soils under the four land use types exhibited significant ($p < 0.05$) variation across land uses but not within soil depth across the land uses (Table 4.4). At the surface layers, relatively higher pH value was recorded in the soils of the natural forest, whereas relatively lower value was recorded in the cropland. The soil organic carbon content was significantly different among land uses, and soil depths within a given land use (Table 4.4).

Across the three depths, significantly higher organic carbon content was found in the natural forest followed by the coffee agroforestry. The cropland, on the contrary, had comparatively lower values of soil organic carbon across its depths. In all the land uses, the soil organic carbon content significantly decreased with soil depth (Table 4.4). Similar to the soil organic carbon content, significantly higher total nitrogen content was found in soils under natural forest followed by the coffee agroforestry (Table 4.4). This is also supported by the highly significant ($P < 0.01$) and positive correlation ($r = 0.96$) between total nitrogen and organic carbon content (Table 4.5). Furthermore, it also decreased with soil depth in all the land uses except the grazing land. Similarly, sand, silt and clay correlated well with SOC (Table 4.5).

The C:N ratio, which is a derived parameter, did not follow the trend of soil organic carbon and total nitrogen with soil depth in all the land uses except the natural forest. Comparatively high values of C:N ratio were recorded in soils of the cultivated and grazing lands as compared to the coffee agroforestry and natural forest soils. Across the land uses, it varied within a relatively narrow range of 11:1 to 17:1.

Table 4.4: Contents of selected soil chemical properties in relation to different land uses and soil depth (mean ± S.D)

Variable	Depth (m)	Land Uses				
		NF	CAF	GL	CR	Overall
pH (H_2O)	0-0.2	7.23 (± 0.16)	6.94 (± 0.04)	6.8 (± 0.49)	6.3 (± 0.04)	**6.91(±0.41)**
	0.2-0.4	7.34 (± 0.16)	6.89 (± 0.1)	6.73 (± 0.64)	6.11 (± 0.05)	**6.89(±0.55)**
	0.4-0.6	7.35 (± 0.08)	6.89 (± 0.09)	6.85 (± 0.52)	6.33 (± 0.09)	**6.94(±0.46)**
	Overall	**7.31(±0.15)c**	**6.91(±0.07)b**	**6.80(±0.48)b**	**6.23(±0.12)a**	
OC (%)	0-0.2	6.38 (± 0.59)	3.39 (± 0.45)	2.71 (± 0.29)	1.86 (± 0.12)	**4.02(2.04) b**
	0.2-0.4	4.22 (± 0.39)	2.93 (± 0.12)	2.23 (± 0.20)	1.63 (± 0.19)	**3.12(1.43) a**
	0.4-0.6	2.89 (± 0.8)	1.94 (± 0.15)	1.68 (± 0.19)	1.15 (± 0.26)	**2.52(1.31) a**
	Overall	**4.80(±1.57)c**	**2.77(±0.66)b**	**2.15(±0.42)ab**	**1.61(±0.34)a**	
TN (%)	0-0.2	0.49 (± 0.11)	0.28 (± 0.07)	0.16 (± 0.01)	0.13 (± 0.01)	**0.33(±0.22)b**
	0.2-0.4	0.36 (± 0.03)	0.21 (± 0.03)	0.17 (± 0.03)	0.1 (± 0.02)	**0.23(±0.11)a**
	0.4-0.6	0.31 (± 0.04)	0.15 (± 0.04)	0.13 (± 0.01)	0.09 (± 0.02)	**0.18(±0.09)a**
	Overall	0.38(±0.17) b	0.21(±0.07) a	0.15(±0.03) a	0.11(±0.02) a	
C:N	0-0.2	12.13 (±0.54)	12.62 (±3.130)	16.58 (±1.03)	14.79 (± 0.75)	**13.33(±2.38)**
	0.2-0.4	12.46 (± 0.39)	14.44 (± 1.97)	13.43 (±1.75)	16.15 (± 2.33)	**13.93(±2.21)**
	0.4-0.6	11.52 (± 1.11)	13.57 (± 2.92)	12.96 (± 1.35)	12.31 (± 0.24)	**14.01(±1.95)**
	Overall	**13.08(±2.04)**	**13.61(±2.37)**	**13.99(±1.73)**	**15.03(±2.28)**	

For each parameter, different letters within a row indicate significant differences ($p<0.5$) with respect to land uses, respectively at each depth ($p<0.05$). TN= total nitrogen, NF= natural forest, CAF= coffee agroforestry, GL= Grazing land and CR=cropland

Table 4.5: Simple correlation analysis results of soil chemical and physical properties

	pH	OC	TN	Sand	Silt	Clay	BD
pH	1.00						
OC	0.81**	1.00					
TN	0.72*	0.96**	1.00				
Sand	0.41	0.70*	0.62*	1.00			
Silt	0.70*	0.64*	0.61*	0.14	1.00		
Clay	-0.71*	-0.89**	-0.81**	-0.81**	-0.69*	1.00	
BD		-0.09		0.12	0.08	-0.14	1.00

** Correlation is significant at the 0.01 level; correlation is significant at the 0.05 level.

4.1.1.3. Deterioration index

The relatively lower deterioration index under the coffee agroforestry could be associated with the relatively better soil management (Appendix 4.28 and Figure 4.1). Studies conducted elsewhere in Ethiopia (e,g., Tassew, 2017) also indicated a high deterioration index under cultivated lands compared with other land uses. The results suggest that most of the smallholder subsistence farming practices in Ethiopia are highly exploitative and undermine the potential of the agriculture sector to sequester carbon and help in mitigating climate change. The results also imply that other alternative land uses with appropriate management strategies (e.g. climate-smart agriculture practices), which enhance the carbon stock and carbon sequestration potential of the lands while minimizing emissions, should be put in place to boost productivity and the subsistence farmers' adaptive capacity against climate change.

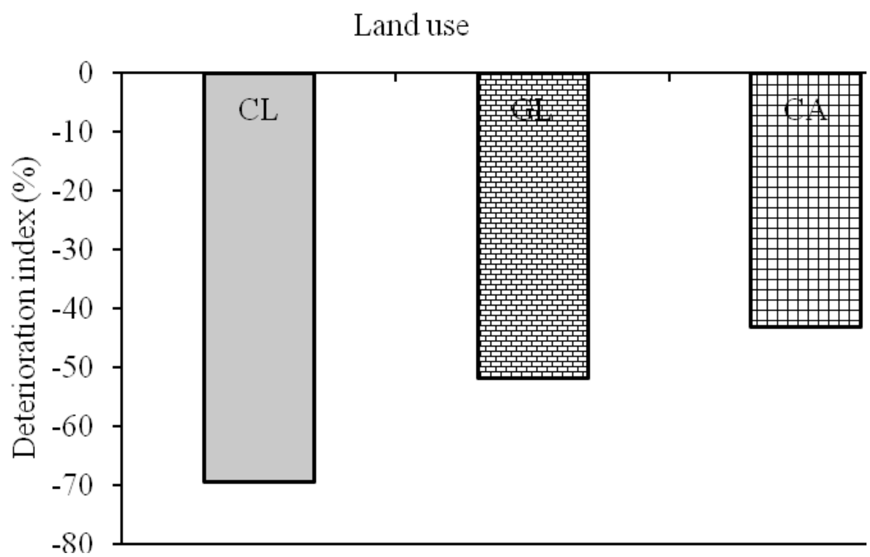


Figure 4.1. Deterioration index of three land uses at Hades Sub-watershed, eastern Ethiopia.

4.1.2. Soil carbon stock under different land use/land cover types

Comparing the four land uses, significantly higher soil organic carbon stock across the three soil depths was recorded in the natural forest. In coffee agroforestry, organic carbon stock was significantly higher compared with crop and grazing lands at 0 - 20 cm and 20 - 40 cm soil depths. However, there was no significant difference in SOC stock of the two land uses (CL; GL) at 20-40 cm soil depth (Table 4.6). Similarly, no significant difference in SOC stock was observed between crop and grazing lands across soil depths. The decline in soil organic carbon was higher at 40-60 cm soil depth than it was at 20-40 cm in all the land uses except the natural forest where the decline was considerable at the 20-40 cm (Table 4.6).

Table 4.6: Soil organic carbon stock (t ha $^{-1}$) in relation to different land uses and soil depths (mean±SE)

Land Uses	Soil depth (cm)		
	0-20	20-40	40-60
Cropland	53.11 (± 8.42)c	48.81 (± 8.04)b	37.03 (± 8.91)b
Grazing Land	57.38 (± 10.29)c	55.4 (± 2.55)b	42.34 (± 4.71)b
Coffee agroforestry	93.78 (± 6.92)b	81.07 (± 16.69)a	60.31(± 15.31)b
Natural forest	141.34 (± 12.32)a	101.36 (± 11.26)a	103 (±23.06)a

.For each parameter, different letters within a column indicate significant differences ($p<0.5$) with respect to land uses at each depth ($p<0.05$).

4.1.3. Vegetation carbon stock

4.1.3.1. Aboveground carbon stock

Due to absence of trees on sample plots under crop and grazing lands, biomass measurement was only made on natural forest and coffee agroforestry land uses. The natural forest was found to have significantly higher biomass carbon stock compared with the coffee agroforestry land use. In the natural forest, 81.5% share of the biomass carbon stock was attributed to the aboveground biomass (Table 4.7). Particularly trees with dbh ≥ 30 cm had contributed the largest carbon (Appendix Table 4.1). In the coffee agroforestry land use, small number of shade trees with small diameter were encountered and measured. Accordingly, the share of aboveground biomass (shade trees and coffee shrub) was 98.29% of the biomass carbon stock of the agro-forestry land use.

4.1.3.2. Root carbon stock

The root carbon stock estimated from the aboveground biomass (20%) was 23.29±3.56 and 3.43±0.34 t ha^{-1} for natural forest and coffee agroforestry, respectively (Table 4.6). Roots are important in terms of carbon balance as they are transferring large amounts of carbon into the soil. In this regard, forests are central in storing carbon below the plough layer, which is more stable.

4.1.3.3. Litter carbon stock

The litter carbon stock in the natural forest and coffee agroforestry was 0.69±0.08 and 0.36±0.04 t ha^{-1}, respectively (Table 4.7). There was no litter on croplands, for crop residue is used for livestock feed, fuel and construction in the study area. Similarly, there was no litter in the grazing land since there was no grass leftover on grazing lands due to heavy grazing and cut and carry system practiced in the study area.

4.1.3.4. Dead wood carbon stock

Dead wood was not observed in the forest area during reconnaissance survey and also not encountered in the sample plots. Hence, no carbon stock measurement was made for dead wood. Similarly, debris' carbon stock was not considered due to the fact that the croplands investigated did not have debris as a carbon pool and the forest debris is often harvested for fuel and structural timber. As mentioned in the area description part, Hades forest is located along Addis-Harar main road where several settlements and small towns are located. People living around the forest are highly dependent on the forest for their energy requirement and frequently collect dead wood from the forest. Although this is an important component of carbon pool in a forest ecosystem, the continuous disturbance of the forest has resulted in complete utilization of any of the trees that are dead.

Table 4.7: Mean vegetation and soil carbon stock, and total carbon stock (t ha $^{-1}$) of different land uses (mean±SE) in Hades Sub-watershed, eastern Ethiopia

Lan use/Land cover	Carbon stock in different Carbon Pools				
	AGC	BGC	LC	SOC	Total carbon
Natural forest	116.46±17.81	23.29±3.56	0.69±0.08	339.`19±21.09	496.26±11.28c
Coffee Agroforestry	17.26±1.9	3.43±0.34	0.36±0.04	249.69 ±28.13	277.38±28.58b
Grazing land				155.13±11.46	155.13±11.46a
Crop land				138.95±25.01	138.95±25.0.1a

.For each parameter, different letters in a column indicate significant differences (p<0.5) with respect to land uses.
AGC= Aboveground carbon, BGC= Belowground carbon, LC = Litter carbon, SOC= Soil organic carbon

4.2. Physical Land Suitability Evaluation for Rainfed Production of Major Crops

4.2.1. Agro-climatic analysis

The Hades Sub-watershed followed the normal growing period type which agrees with the FAO working definition demonstrating a humid period and a period where precipitation is less than the evapotranspiration. The analysis results of the long-term average monthly rainfall and ET_o data using both the graphic and linear interpolation methods revealed that, the rain and rainy season start on 2nd decade of March and end on 1st decade of October (Figure 4.1 and Appendix Tables 4.2 and 4.3). On the other hand, the humid period, the time period during which rainfall exceeds potential evapotranspiration, starts on 1st decade of April and ends on 2nd decade of September. Hence, the period commencing from the start of growing period extending to the end of rains in the study area covers around 213 days according to the computation made using the indicated methods. In addition, about 32 additional days, calculated based on ETo values of the period between October 12 and November 12, are required to consume the assumed 100 mm of water expected to be stored within the soil at the end of the rains. Therefore, the LGP extends up to 2nd decade of November, which is a total of 239 days.

It is usually recommended to start sowing as early as possible in the growing period. FAO (1983) further recommends starting of planting in the first decade that receives 30 mm of rain. Therefore, from the rainfall data analysis the first decade that receives 30 mm or more rainfall is the 1st decade of April. This indicates that, for Hades Sub-watershed, the planting time should start on 1stdecade of April (April 1 to 10). As it is illustrated in Figure 4.2, the study site is characterized by bi-modal rainfall pattern, which is common in most parts of the country. The first period is locally called *Belg*, small rainy season, and this season covers the period between March/April to May. This small rainy season is followed by a dry period in the month of June. Farmers commonly plant maize and sorghum during this small rainy season. The crops often face moisture deficit stress during this dry period. The second and main season is locally called *Kiremt*, and often stretches from July to September with the highest rainfall received during the months of July and August (Figure 4.2). It is this period that provides water for storage in the soil system and is the main planting time for crops that have relatively shorter cycles than maize and sorghum.

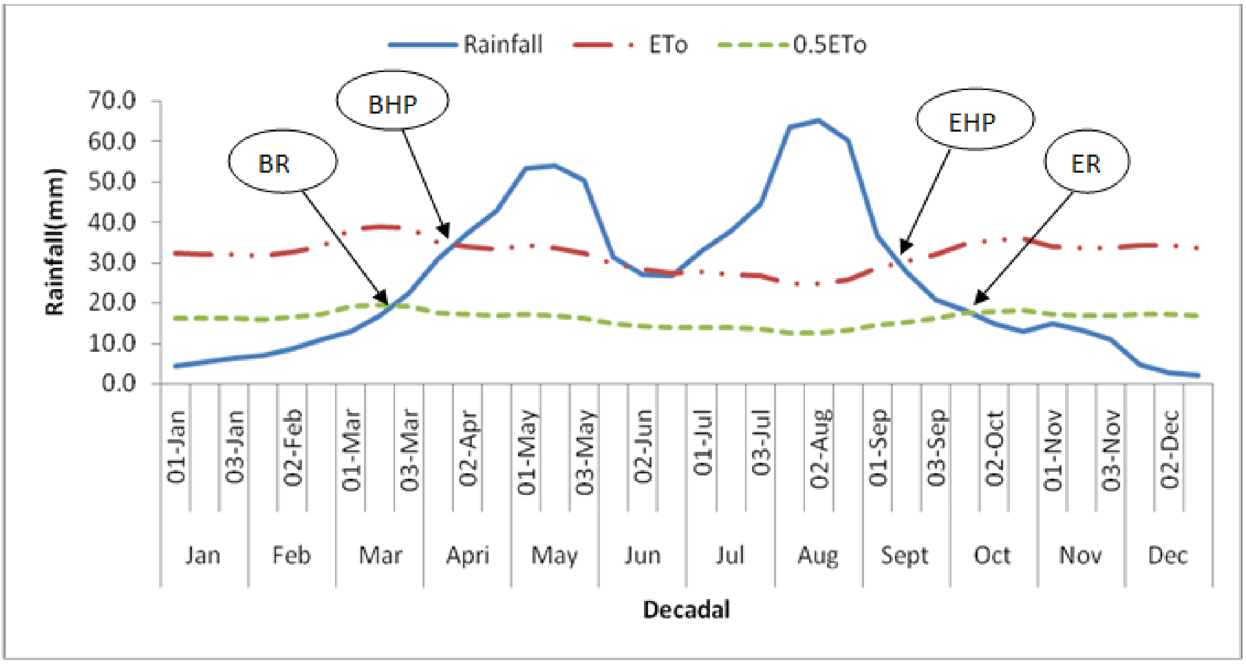


Figure 4.2: Graph showing length of growing period for Hades Sub-watershed in eastern Ethiopia.

4.2.2. Overall land suitability for the selected land utilization types

4.2.2.1. Sorghum

The major limiting attributes for successful production of late-maturing sorghum in the study area, under the current low-level of management, include steep slope (SMU3), imperfect drainage (SMU1, 2, and 4), shallow effective soil depth (SMU2), low organic matter (all the SMUs), low available P (SMUs 1, 2, and 3), and low temperature during the growing cycle of the crop (Table 4.8). The overall suitability classes for climate, and soil and landscape attributes are presented in Appendix Tables 4.4 and 4.5, respectively. Similarly, soil and landscape suitability for individual soil mapping units are presented in Appendix Table 4.6 for all crops. The weighted organic carbon and available P levels of soils under SMUs 1, 2, and 3 are moderately suitable (S2) for sorghum production since it requires higher levels of these attributes. Similarly, except the SMU3, the drainage condition of the other three mapping units is not good enough for optimum growth of sorghum. As a result, it is marginally suitable. The steep slope of SMU3 is another landscape feature which makes the area marginally suitable for sorghum production. Sorghum requires higher temperature than the mean temperature of the growing period in the study area. Because of this, the temperature of the study area is marginally suitable. The effective depth of the SMU2 is also shallower (moderately suitable) than what is considered highly suitable for sorghum production. From among the soil and landscape and climate attributes identified as less optimal, organic matter and P levels can easily be managed, while the others are more difficult to manage. As a consequence, the overall suitability of the study area for sorghum production after improvement (potential suitability) remains marginally suitable (S3c) because of the low mean temperature during the crop's cycle.

4.2.2.2. Maize

Soil and landscape and climate requirements of maize are more or less similar to that of sorghum. The major limitations include steep slope (SMU3), imperfect drainage (SMUs 1, 2, and 4), shallow effective root depth (SMU2), coarse soil texture (SMUs 1, 2, and 4), high soil pH (SMU 2, 3, and 4), low organic matter (all SMUs), low available P (SMU1, 2, and 3), and low temperature during the crop cycle (Table 4.8, Appendix Tables 4.4-4.6). The soil fertility limitations are related to low levels of organic matter and available P in all the SMUs except SMU4 and high pH in SMUs 2-4. Coarse soil texture (sandy clay) is also a less optimal soil attribute in all the SMUs except SMU3, which is optimal. The shallow effective root depth (94 cm) is also moderately suitable for production of maize. The drainage class of all the SMUs except SMU3 is also marginally suitable because of its imperfect drainage, which may limit availability of adequate oxygen for root respiration and root ramification. The steep slope of SMU3 is also less optimal for maize production. Similar to sorghum, the mean temperature of the growing period is much colder than what is considered optimum (highly suitable) for successful maize production. As a result, temperature of the study area is marginally suitable for production of maize at Hades Sub-watershed. Because of these limitations, the current overall suitability class for maize production is 'marginally suitable- S3 (cw) for SMUs 1, 2 and 3 and S3(c) for SMU 4. Since the low temperature of the study area cannot be managed easily, the overall potential suitability also remains 'marginally suitable-S3(c)' for all the mapping units (Table 4.8). The coarser texture in soils under SMUs 1, 2, and 4, the shallow effective root depth in SMU 2 and the steep slope of SMU3 are also permanent in nature.

4.2.2.3. Coffee

The major limiting attributes for successful production of coffee in the study area include imperfect drainage (SMUs 1, 2 & 4), low precipitation during the growing period (SMU 1,2,3 &4), high soil pH-H_2O (SMUs 2 & 3), shallow effective root depth (SMU 2), steep slope (SMU 3), and a coarser soil texture (SMU 3) (Table 4.8, Appendix Tables 4.4-4.6). Moreover, the mean temperature of the growing period is low for successful coffee production. While the high pH and drainage are correctable with reasonable cost, the others are all permanent limitations. Owing to these limitations, the maximum current overall land suitability class for production of coffee is 'marginally suitable (S3wc for SMU 1 and 4, S3wsfc for SMU 2 and S3fc for SMU 3). The potential suitability also remains 'marginally suitable (S3sc)' due to low precipitation and shallow soil depth of the study area (Table 4.8).

Table 4.8: Overall land suitability classes for rainfed production of late-maturing sorghum and maize, coffee, finger millet, and upland rice crops at Hades sub-watershed, eastern Ethiopia

SMU*	Overall suitability class									
	Sorghum (180 – 240 days cycle)		Maize (180-210 days cycle)		Coffee arabica		Finger Millet (120 - 150 days cycle)		Upland rice (120 days cycle)	
	Act	Pot	Act	Pot	Act	Pot	Act	Pot	Act	Pot
SMU1	S3(c)	S3 (c)	S3(cw)	S3(c)	S3 (wc)	S3 (c)	S3 (c)	S3 (c)	N2 (c)	N2 (c)
SMU2	S3(c)	S3 (c)	S3(wfc)	S3(c)	S3(wsfc)	S3(sc)	S3 (c)	S3 (c)	N2 (c)	N2 (c)
SMU3	S3(c)	S3 (c)	S3(c)	S3(c)	S3(fc)	S3(c)	S3(tc)	S3(tc)	N2 (c)	N2 (c)
SMU4	S3(wfc)	S3 (c)	S3(c)	S3(c)	S3(wc)	S3 (c)	S3(c)	S3(c)	N2 (c)	N2 (c)

*Soil Mapping Unit; Act = actual; Pot = potential; w = wetness; f = fertility; t = topography; c = climate; s = physical soil condition

4.2.2.4. Upland rice

The major limiting attributes for successful production of upland rice in the study area under rain fed and low-level of management include high precipitation and low mean temperature during the growing period, slightly high pH (SMU 2), steep slope, poor drainage, and coarser soil texture (SMU3) (Table 4.8, Appendix Tables 4.4-4.6). Unlike for the other crops, SMUs 1 and 4 are highly suitable in terms of soil and landscape attributes. Under the low level of management, all the limitations, except the slightly high pH in SMU2, are considered permanent, which makes the maximum overall current land suitability class permanently not suitable (N2 c for SMUs 1, 2, 3 and 4) for production of upland rice (Table 4.8). Similarly, the sub-watershed will remain potentially not suitable (N2c) for production of upland rice.

4.2.2.5. Finger millet

The major limitations for successful production of finger millet in the study area under rainfed and low-level of management are low mean temperature, steep slope (SMU 3), poor drainage (SMUs 1, 2, and 4), excessive drainage (SMU 3), and slightly high pH (SMU2) (Table 4.8, Appendix Tables 4.4-4.6). The low mean temperature and the steep slope are marginally suitable for finger millet, while all the other identified limitations are within the range of moderately suitable class. Because of these limitations, the current overall suitability class is 'marginally suitable (S3c for SMU 1, 2 and 4, and S3tc for SMU 3) for finger millet production (Table 4.8). Due to the permanent nature of the mentioned limitations, the sub-watershed remains potentially (S3tc) marginally suitable for production of finger millet.

4.2.3. Mapping land suitability

The area under the above-discussed suitability classes for the respective land utilization types (LUTs) was mapped using ArcGIS version 10.4.1 software. The map shows, for each LUT, the area covered by the respective suitability classes under the current and future management conditions. Accordingly, all the 553 ha of the agricultural land in the study area is marginally suitable for production of late-maturing sorghum, late-maturing maize, coffee, and finger millet under both current and future management conditions. Table 4.9 illustrates the area occupied by the respective suitability classes in each soil mapping unit for sorghum, maize, coffee, finger millet, and upland rice. Figures 4.3-4.7 show the distribution of the suitability classes for sorghum, maize, coffee, finger millet, and upland rice, respectively. On the other hand, all the 553 ha of the agricultural land is not suitable for production of upland rice under current and future management scenarios.

Table 4.9: Area coverage of land suitability for cultivation of late-maturing sorghum, maize, coffee, millet, and upland rice under rainfed conditions at Hades sub-watershed, eastern Ethiopia

SMU*	Actual land suitability		Potential land suitability		Area (ha)
	Class	Code	Class	Code	
Late-maturing Sorghum (180-240 days cycle)					
SMU 1	Marginally Suitable	S3(c)	Marginally Suitable	S3(c)	201
SMU 2	Marginally Suitable	S3(c)	Marginally Suitable	S3(c)	79
SMU 3	Marginally Suitable	S3(c)	Marginally Suitable	S3(c)	107
SMU 4	Marginally Suitable	S3(wfc)	Marginally Suitable	S3(c)	166
Late-maturing Maize (180-210 days cycle)					
SMU 1	Marginally Suitable	S3(cw)	Marginally Suitable	S3(c)	201
SMU 2	Marginally Suitable	S3(wfc)	Marginally Suitable	S3(c)	79
SMU 3	Marginally Suitable	S3(c)	Marginally Suitable	S3(c)	107
SMU 4	Marginally Suitable	S3(c)	Marginally Suitable	S3(c)	166
Coffee					
SMU1	Marginally Suitable	S3wc	Marginally Suitable	S3c	201
SMU2	Marginally Suitable	S3wsfc	Marginally Suitable	S3sc	79
SMU3	Marginally Suitable	S3fc	Marginally Suitable	S3c	107
SMU4	Marginally Suitable	S3c	Marginally Suitable	S3c	166
Finger Millet (120-150 days cycle)					
SMU1	Marginally Suitable	S3c	Marginally Suitable	S3c	201
SMU2	Marginally Suitable	S3c	Marginally Suitable	S3c	79
SMU3	Marginally Suitable	S3tc	Marginally Suitable	S3c	107
SMU4	Marginally Suitable	S3c	Marginally Suitable	S3c	166
Upland Rice (120 days cycle)					
SMU1	Not Suitable	N2c	Not Suitable	N2c	201
SMU2	Not Suitable	N2c	Not Suitable	N2c	79
SMU3	Not Suitable	N2c	Not Suitable	N2c	107
SMU4	Not Suitable	N2c	Not Suitable	N2c	166
SMU5	Forest land	NA**	NA	NA	418

SMU* = Soil Maping Unit: NA** = Not Applicable

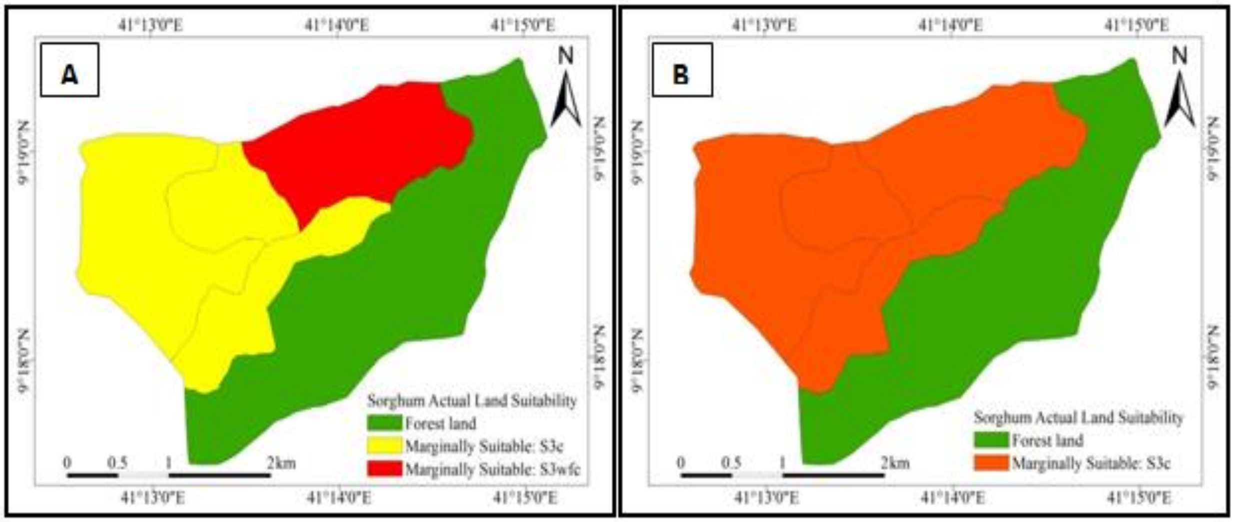


Figure 4.3: Actual (A) and potenial (B) land suitability map for late-maturing sorghum variety at Hades Sub-watershed, eastern Ethiopia.

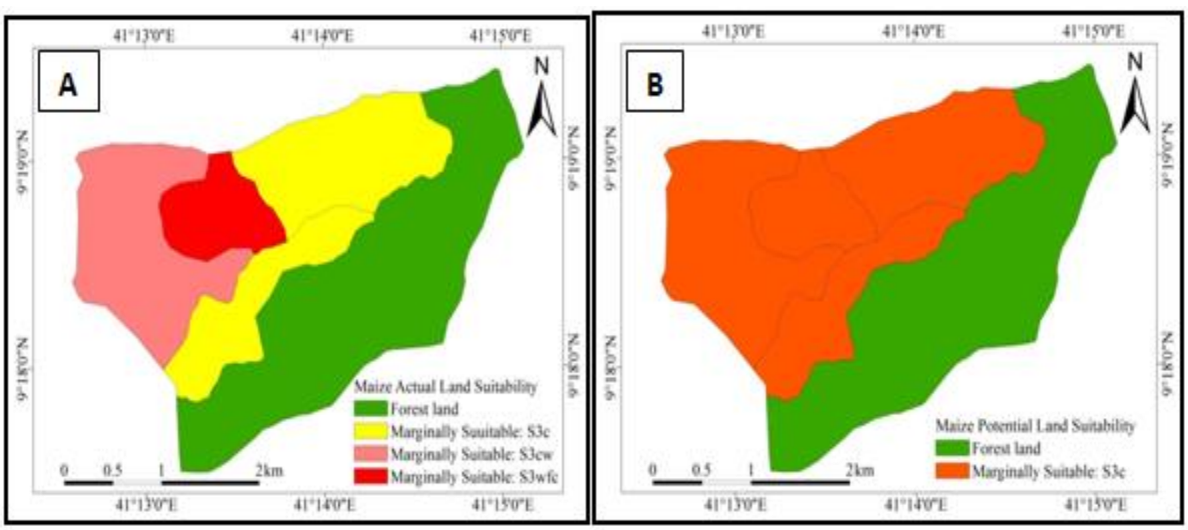


Figure 4.4: Actual (A) and potential (B) land suitability map for late-maturing maize variety at Hades Sub-watershed, eastern Ethiopia.

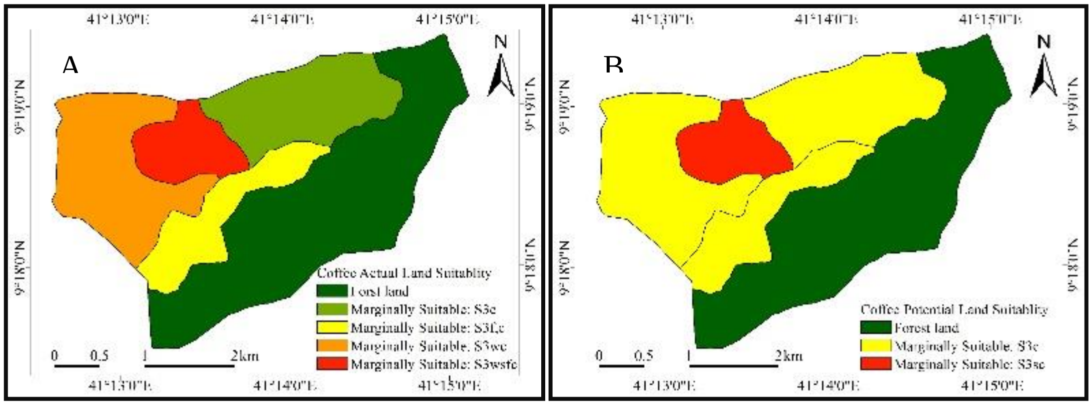


Figure 4.5: Actual (A) and potenial (B) land suitability map for Arabica coffee at Hades Sub-watershed, eastern Ethiopia.

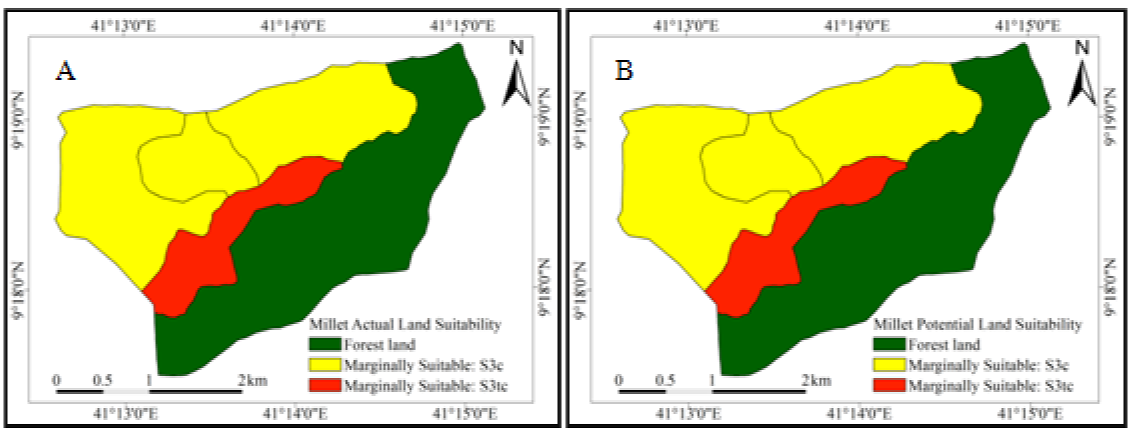


Figure 4.6: Actual (A) and potenial (B) land suitability map for millet at Hades Sub-watershed, eastern Ethiopia.

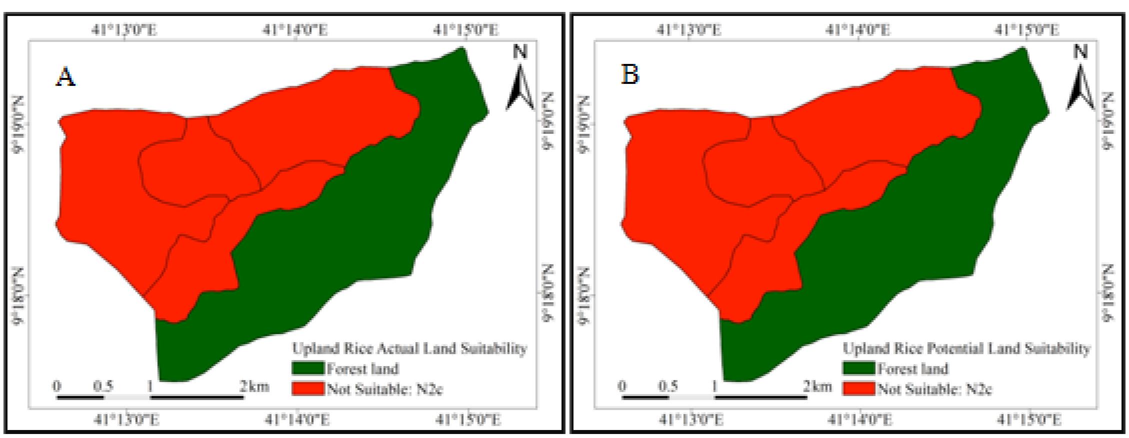


Figure 4.7: Actual (A) and potenial (B) land suitability map for upland rice at Hades sub-watershed, eastern Ethiopia.

4.3. Projection of Carbon Sequestration Potential of Selected Land Utilization Types under Projected Climate Over the Coming 50 Years

4.3.1. Projected climate

4.3.1.1. Projected average annual rainfall

Figure 4.8 illustrates percentage rainfall deviation from the baseline under RCP4.5 for the Near- and Mid-centuries. Appendix Table 4.7 illustrates temperature and rainfall projected using different models under the two time slices and RCPs. Compared to the baseline, high average rainfall percentage variability (> 30%) was observed during the *Kiremt* (the main rainy season of the country) season (JJAS) under RCP4.5 Near-century for MOHC-HadGEM2-ES climate model. The other three models (CNRM-CERFACS-CNRM-CM5, MPI-M-MPI-ESM-LR and ICHEC-EC-Earth) and the MME (ensemble) showed lower percentage of rainfall variability for the same season. It was also noted that JJAS rainfall will decrease during the Near-Century under RCP4.5.

For Mid-century (2040-2069) of RCP4.5, the seasonal rainfall analysis indicated that CNRM-CERFACS-CNRM-CM5 model projected slight increment of rainfall during JJAS, while the other models and MME projected reduction of rainfall for the same season with lower percentage rainfall variability (< 20%). On the other hand, the *Belg* season's (FMAM) percentage variability was found to be higher (>30%) for MOHC-HadGEM2-ES climate model, while the other models and MME predicted low rainfall variability (< 20%) (Figure 4.8).

Under RCP8.5 climate scenario, MOHC-HadGEM2-ES and MME models projected high variability (> 30%) of JJAS rainfall during Near-century, while the other three models predicted lower variability of main season rainfall. On the other hand, all the models, except the ICHEC-EC-Earth model, predicted a reduction of FMAM rainfall. The percentage deviation was high (>30) for ICHEC-EC-Earth model, while it was low for the other three models and MME (Figure 4.9).

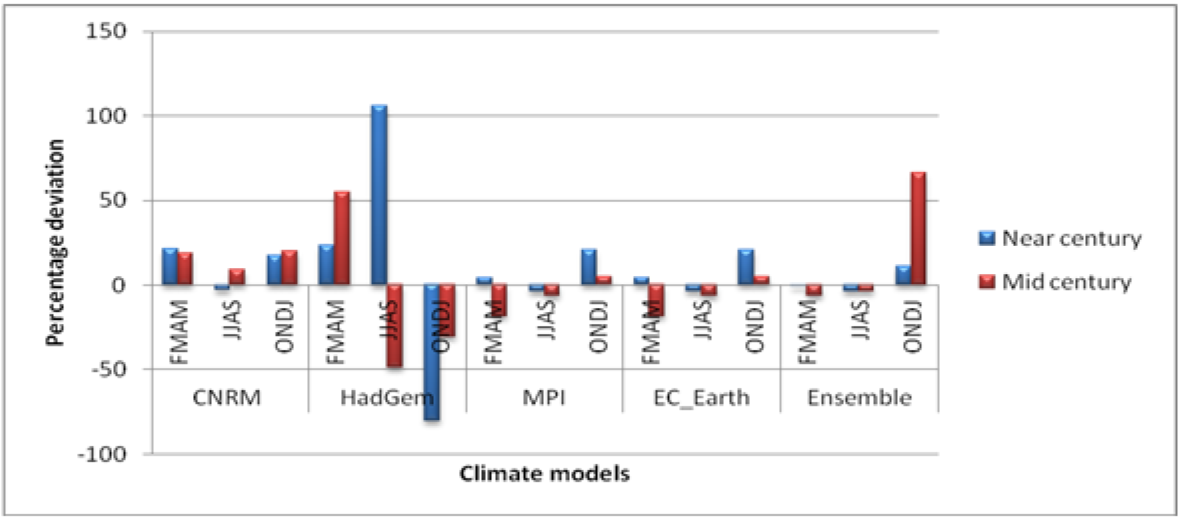


Figure 4.8: Percentage rainfall deviation from the baseline under RCP4.5 for near and mid centuries as projected by different models (CNRM_CMS = CNRM-CERFACS-CNRM-CM5; HadGem_ES = MOHC-HadGEM2-ES; MPI_MSR_LR = MPI-M-MPI-ESM-LR; EC-Earth = ICHEC-EC-Earth; MME= Multi Model Ensemble).

The Mid-century rainfall under RCP8.5 indicated high variability for the JJAS under MOHC-HadGEM2-ES climate model and MME (Figure 4.9). The other models predicted reduction of rainfall during Mid-century of RCP8.5 but with low percentage variability from the base line. For FMAM, the percentage rainfall deviation was low for all the climate models except for the MME.

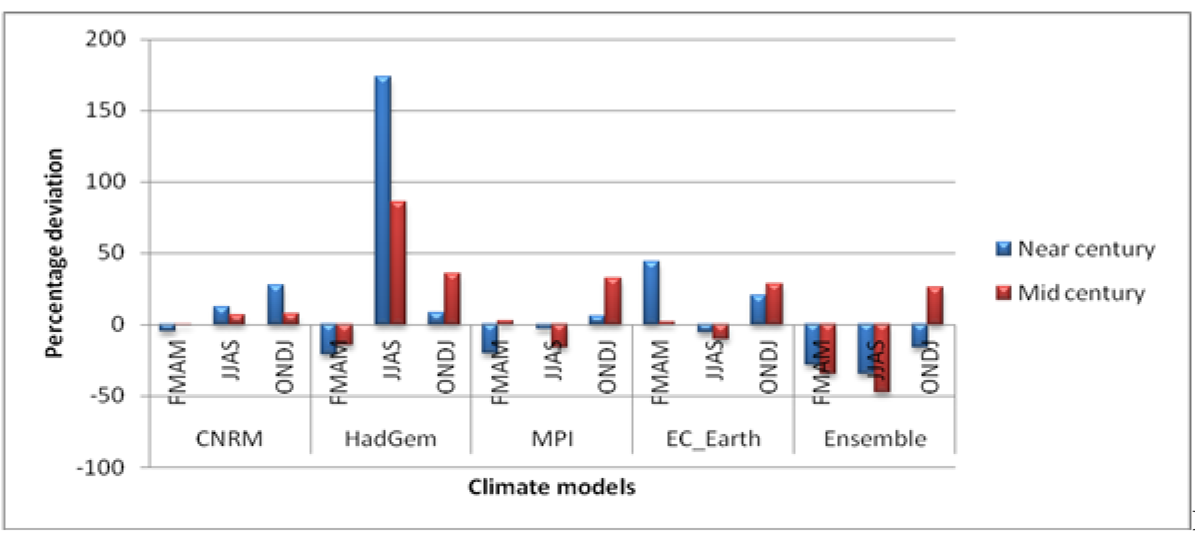


Figure 4.9: Percentage rainfall deviation from the baseline under RCP8.5 for near and mid centuries

(CNRM_CMS = CNRM-CERFACS-CNRM-CM5; HadGem_ES = MOHC-HadGEM2-ES; MPI_MSR_LR = MPI-M-MPI-ESM-LR; EC-Earth = ICHEC-EC-Earth; MME= Multi Model Ensemble)

It was noted that percentage deviation of rainfall showed variation across the models employed and RCPs considered. Compared to the other models, MOHC-HadGEM2-ES model generated the highest increment of rainfall for JJAS under RCP8.5. On the contrary, the same model predicted lower rainfall for JJAS under RCP4.5. The MME, on the other hand, indicated reduction of rainfall for JJAS and FMAM seasons. However, most of the models indicated an increase in rainfall during Near-century under RCP4.5. Under RCP8.5, all the models except CNRM-CERFACS-CNRM-CM5 indicated reduction of rainfall during Mid-century.

4.3.1.2. Seasonal temperature total

The minimum temperature (T_{min}) showed increment compared to the baseline for all seasons and time slices considered under RCP4.5 (Figure 4.10). With the exception of MPI-M-MPI-ESM-LR model where the highest T_{min} increment was for Near-century compared to the Mid-century, the other models generated the highest increment in Mid-century than Near-century temperature. The result depicted that all the models yielded < 20% deviation of the minimum temperature from the baseline. Besides, percentage deviation of the minimum temperature from the baseline was higher for ONDJ compared to the two rainy seasons (JJAS and FMAM) in the study area.

Under RCP8.5 CNRM-CERFACS-CNRM-CM5, MOHC-HadGEM2-ES, and ICHEC-EC-Earth models projected higher minimum temperature during the Near-century as compared to the Mid-century (Figure 4.11). Unlike under RCP4.5, the minimum temperature projected by the MPI-M-MPI-ESM-LR model under RCP8.5 was almost similar for Near- and Mid-century . In the case of MME, T_{min} showed reduction for the Near-century and increased for the Mid-century. In all the climate models, higher percentage deviation of the minimum temperature was observed during ONDJ than JJAS and FMAM.

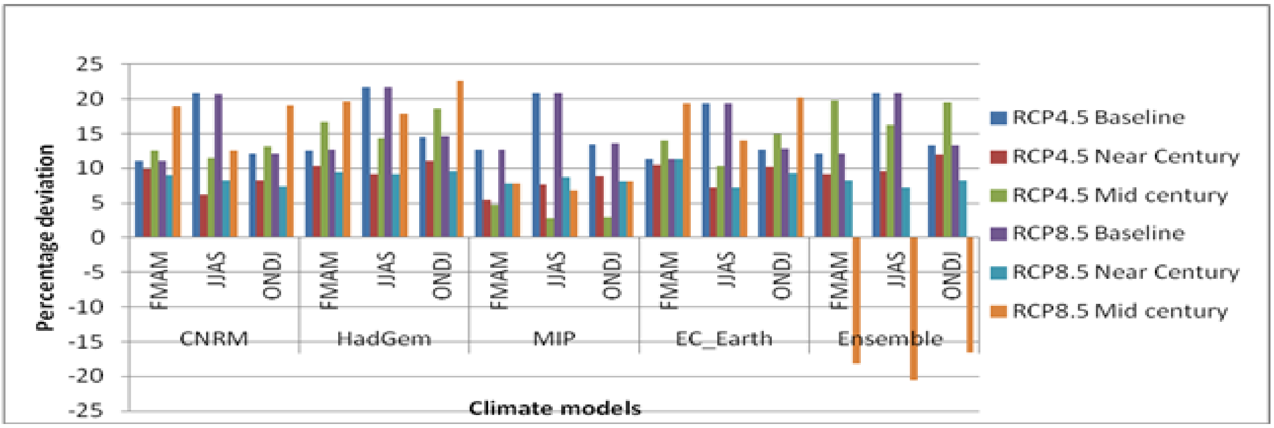


Figure 4.10: Percentage deviation of minimum temperature from the baseline under RCP4.5 and RCP8.5 emission scenarios.

In the study area, the magnitude of maximum temperature change varied with the RCPs and time slices considered. All the climate models projected an increase in maximum temperature in the Near- and Mid-centuries with the exception of the Near-century for FMAM in CNRM-CERFACS-CNRM-CM5 climate model and for Mid-century of MME under both RCP4.5 and RCP8.5.

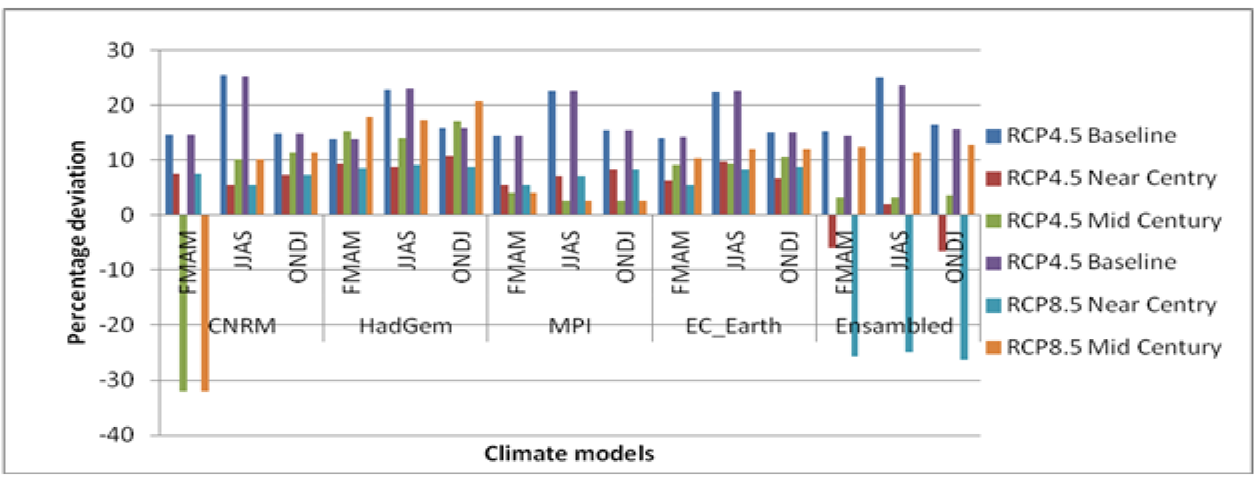


Figure 4.11: Percentage deviation of maximum temperature (^{o}C) from the baseline under RCP4.5 and RCP8.5 emission scenarios.

4.3.1.3. Model calibration and validation results

The simulated grain yield values of maize and sorghum remarkably agreed well with the observed values as the agreement index (d statistic) values were 0.99 for each crops (Table 4.10). The *d* value indicates similarity of the simulated yield with the observed one. The root mean square error normalized (RMSEN) value indicates that maize and sorghum yields were estimated with high accuracy since it was less than 10%. The E value of sorghum and maize was 0.99 for each crop, which was similar with the d value indicating the high performance of the model.

Table 4.10: Statistical evaluation of AquaCrop model calibration and validation for maize (BH661) and sorghum (Muyira-1) biomass yield

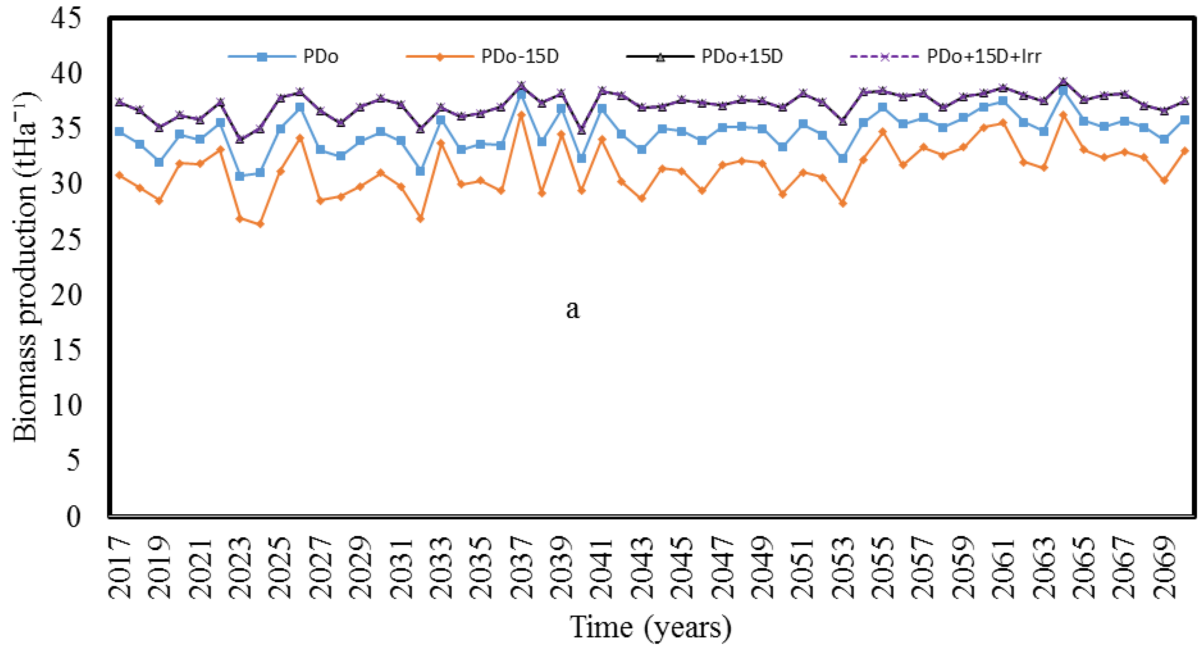
Statistical parameters	Model calibration		Model validation	
	Maize	Sorghum	Maize	Sorghum
MAE	0.29	0.11	0.49	0.54
RMSEN	6.72	8.42	2.53	5.60
E	na	na	0.99	0.99
d	na	na	0.99	0.99

4.3.2. Projected biomass production of sorghum and maize

4.3.2.1. Sorghum (Muyira-1)

The results revealed that, with the exception of the MPI_M_MPI_ESM_LR climate model under RCP8.5 , all the other climate models under both RCPs projected reductions in sorghum biomass if planting is undertaken 15 days earlier (PD_o-15D) than the actual planting time (PD_o) (Figures 4.12-4.16 and Appendix Tables 4.8-4.17). The adaptation options considered resulted in reduction of biomass by 0.13 to 3.87 t ha^{-1} (under RCP4.5) and 0.1 to 3.91 $x10^3$ t ha^{-1} (RCP8.5) for early planting (PD_o-15D) across all the climate models. On the contrary, delaying planting by 15 days (PD_o+15D) produced as equal biomass as delaying planting by 15 days with supplementary irrigation (PD_o+15D+IR) across the climate models and RCPs considered, indicating that supplementary irrigation may not be required for increasing biomass yield of the selected sorghum variety.

Under RCP 4.5, CNRM-CERFACS-CNRM-CM5, ICHEC-EC-Earth and MME climate models projected that sorghum biomass yield could be increased by up to up to 28.10 t ha^{-1} against the baseline if delayed planting (PD_o+15D) is combined with supplementary irrigation. Contrary to this, MOHC-HadGEM2-ES and MPI-M-MPI-ESM-LR climate models projected a slight reduction (0.01 to 0.02 t ha^{-1}) in sorghum biomass yield if the same adaptation measure is used under RCP4.5.



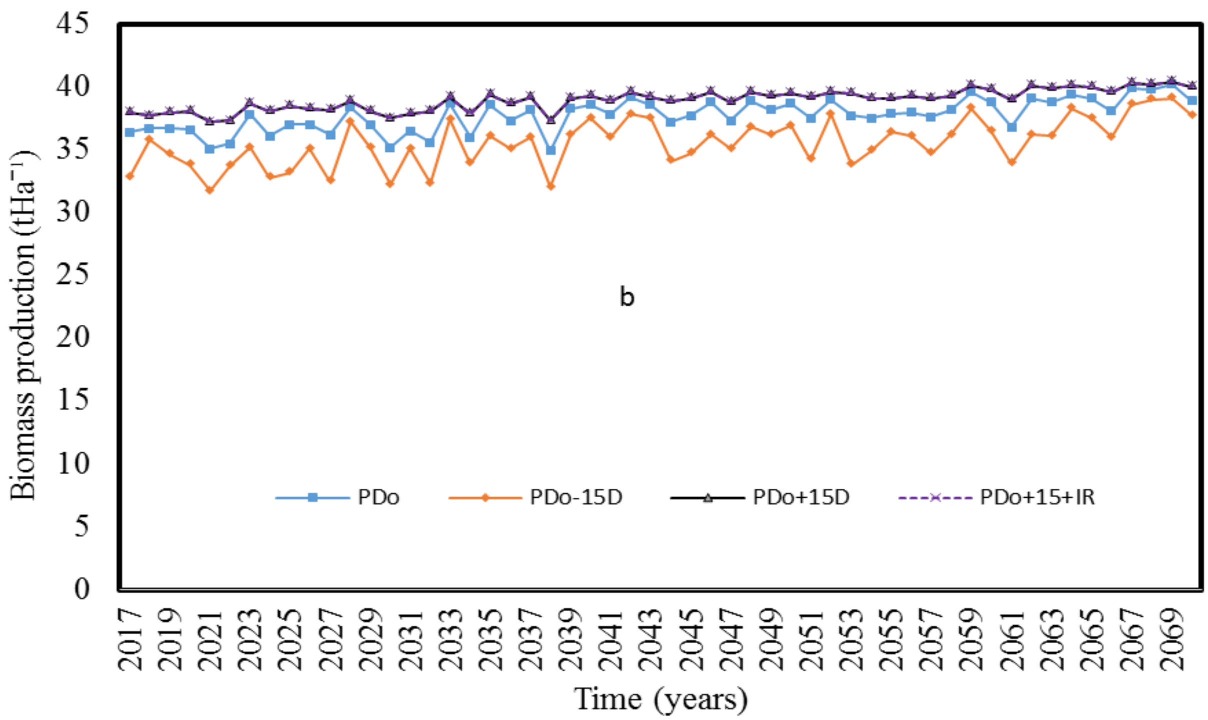


Figure 4.12: Projected sorghum (Muyira-1) biomass yield under RCP4.5 (a) and RCP8.5 (b) for CNRM_CERFACS_CNRM_CM5 climate model (PD_o = reference sowing date (baseline), PD_o-15D = 15 days before the baseline, PD_o+15D = 15 days after the baseline, PD_o-15D +IR = 15 days after the baseline with supplementary irrigation

With regard to time slices, all the climate models, except CNRM-CERFACS-CNRM-CM5 and ICHEC-EC-Earth models under RCP4.5, projected an increasing trend of biomass yield with time. The multi model ensemble (MME), however, indicated variation in biomass production during Near-century for all the models and adaptation options except for PD_o+15D and PD_o +15 D + IR, in which case the two generated the same amount of sorghum biomass in the time slice considered. On the other hand, the multi model ensemble (MME) indicated absence of difference in biomass production in all the adaptation options in the Mid-century of both RCP4.5 and RCP 8.5.

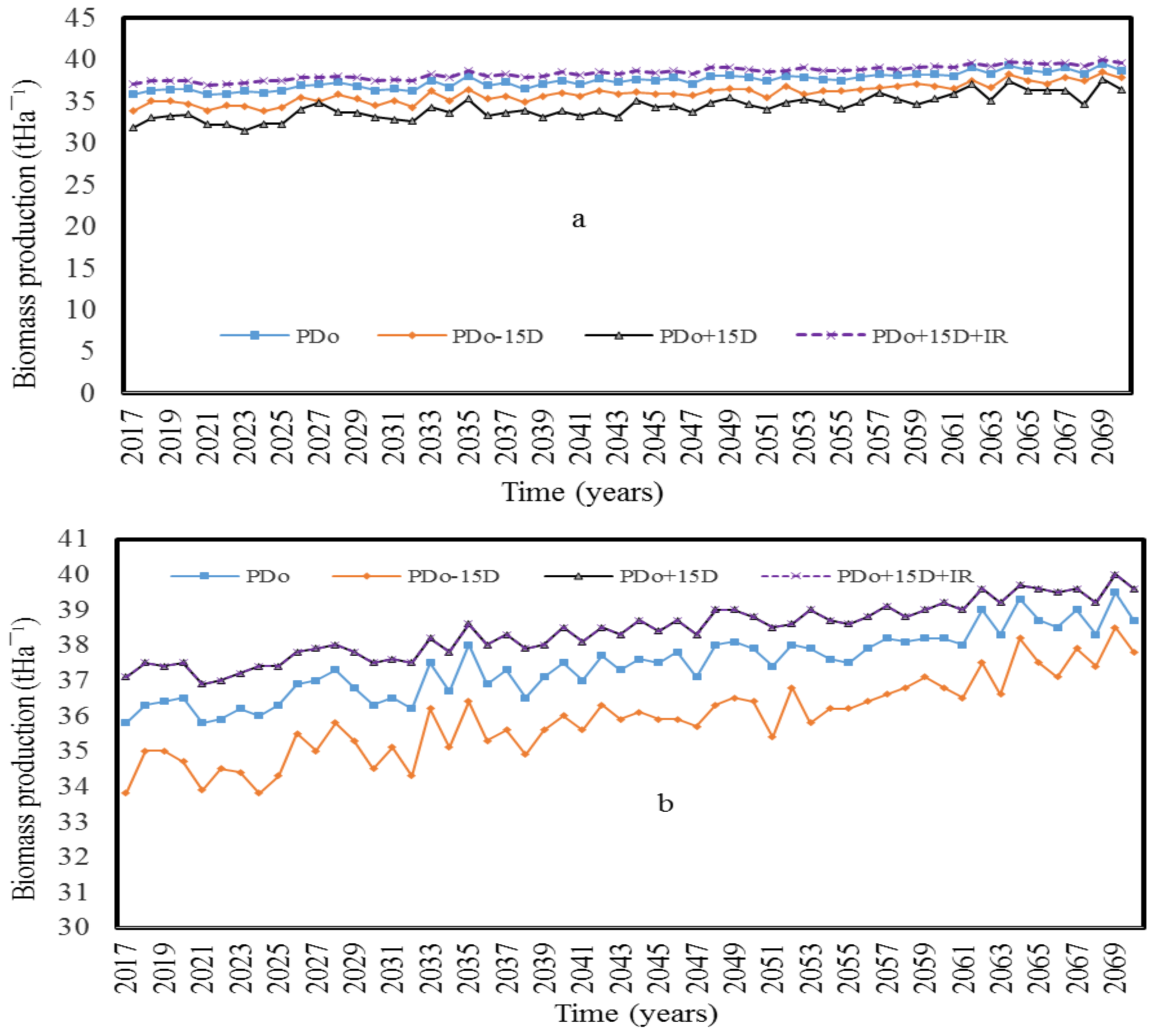


Figure 4.13: Projected sorghum (Muyira-1) biomass yield under RCP4.5 (a) and RCP8.5 (b) for Multi Model Ensemble climate model (PD_o = reference sowing date (baseline), PD_o-15D = 15 days before the baseline, PD_o+15D = 15 days after the baseline, PD_o-15D +IR = 15 days after the baseline with supplementary irrigation.

With regard to time slices, all the climate models, except CNRM-CERFACS-CNRM-CM5 and ICHEC-EC-Earth models under RCP4.5, projected an increasing trend of biomass yield with time. The multi model ensemble (MME), however, indicated variation in biomass production during near century for all models and adaptation options except PD_o+15D and PD_o +15 D + IR, in which case the two generated the same amount of sorghum biomass in the time slice considered. On the other hand, the multi model ensemble (MME) indicated absence of difference in biomass production in all adaptation options in the Mid-century of both RCP4.5 and RCP 8.5.

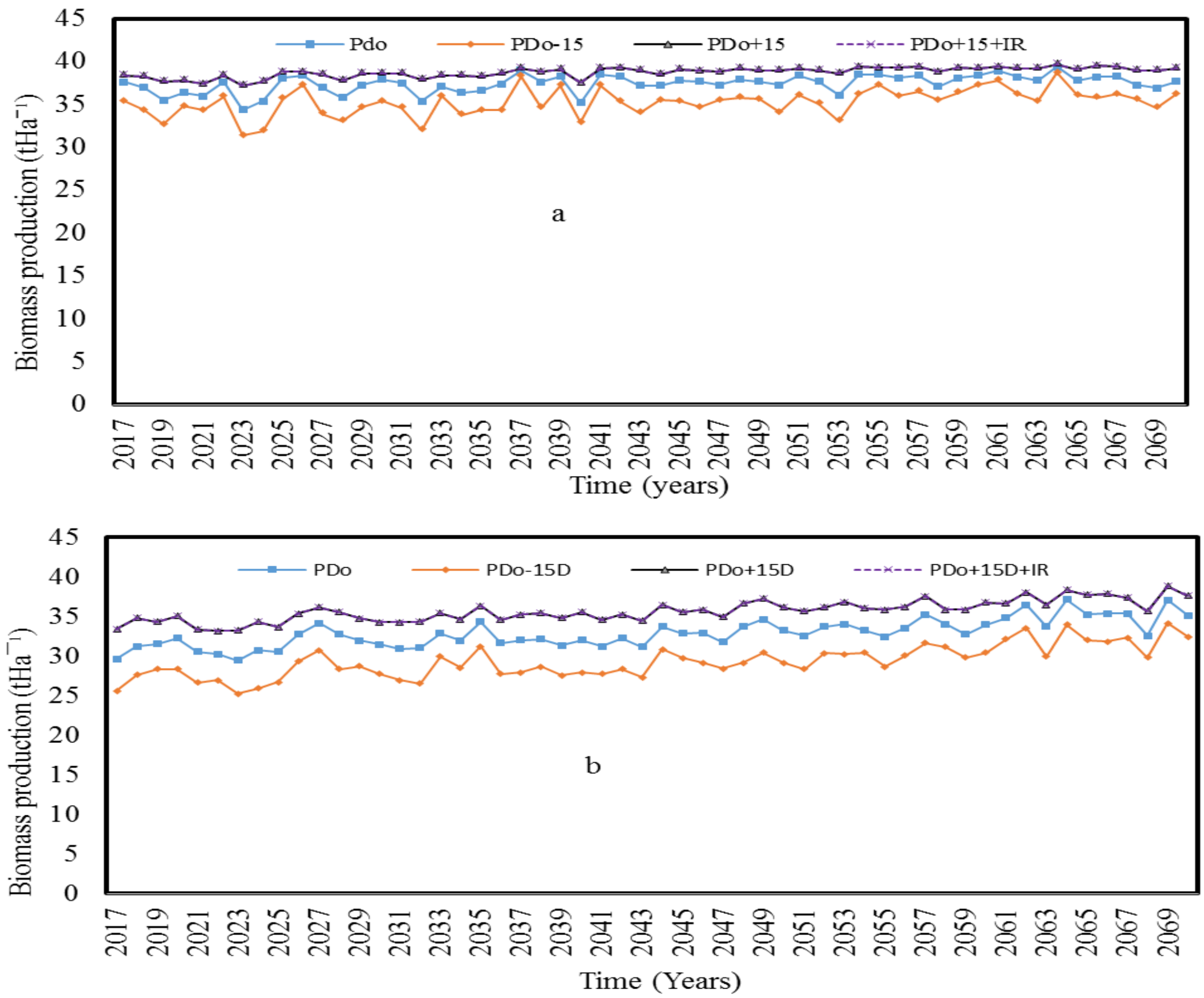
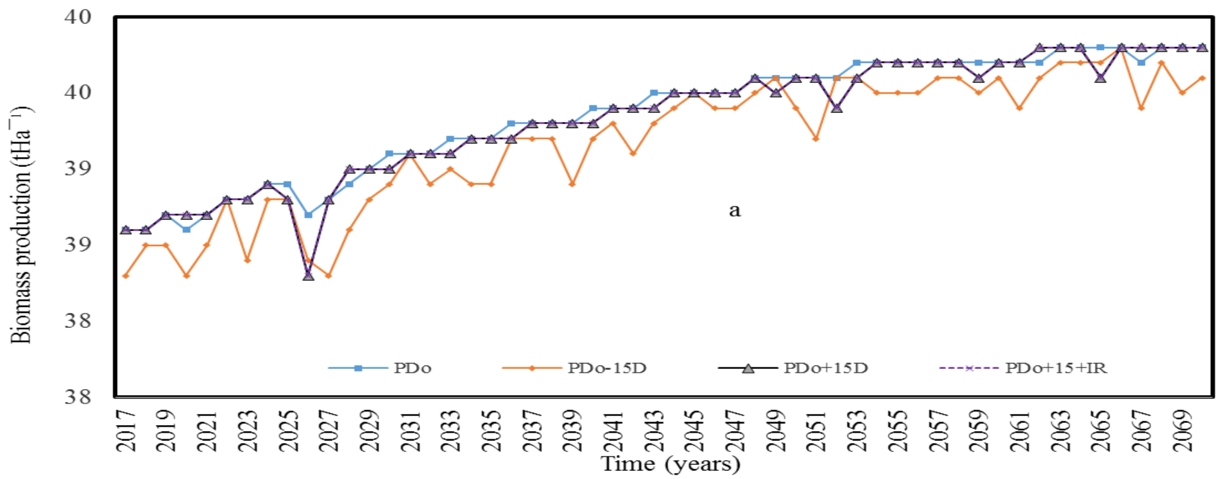


Figure 4.14: Projected sorghum (Muyira-1) biomass yield under RCP4.5 (a) and RCP8.5 (b) for ICHEC-EC-Earth climate model (PD_o = reference sowing date (baseline), PD_o-15D = 15 days before the baseline, PD_o+15D = 15 days after the baseline, PD_o-15D + IR = 15 days after the baseline with supplementary irrigation.



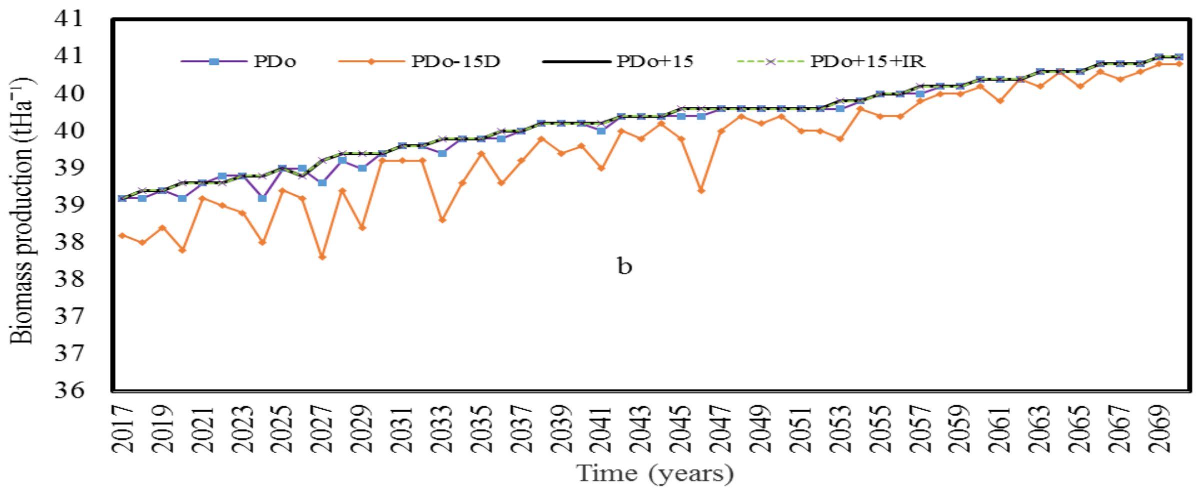


Figure 4.15: Projected sorghum (Muyira-1) biomass yield under RCP4.5 (a) and RCP8.5 (b) for MOHC_HadGem2_ES climate model (PD_o = reference sowing date (baseline), PD_o-15D = 15 days before the baseline, PD_o+15D = 15 days after the baseline, PD_o-15D +IR= 15 days after the baseline with supplementary irrigation.

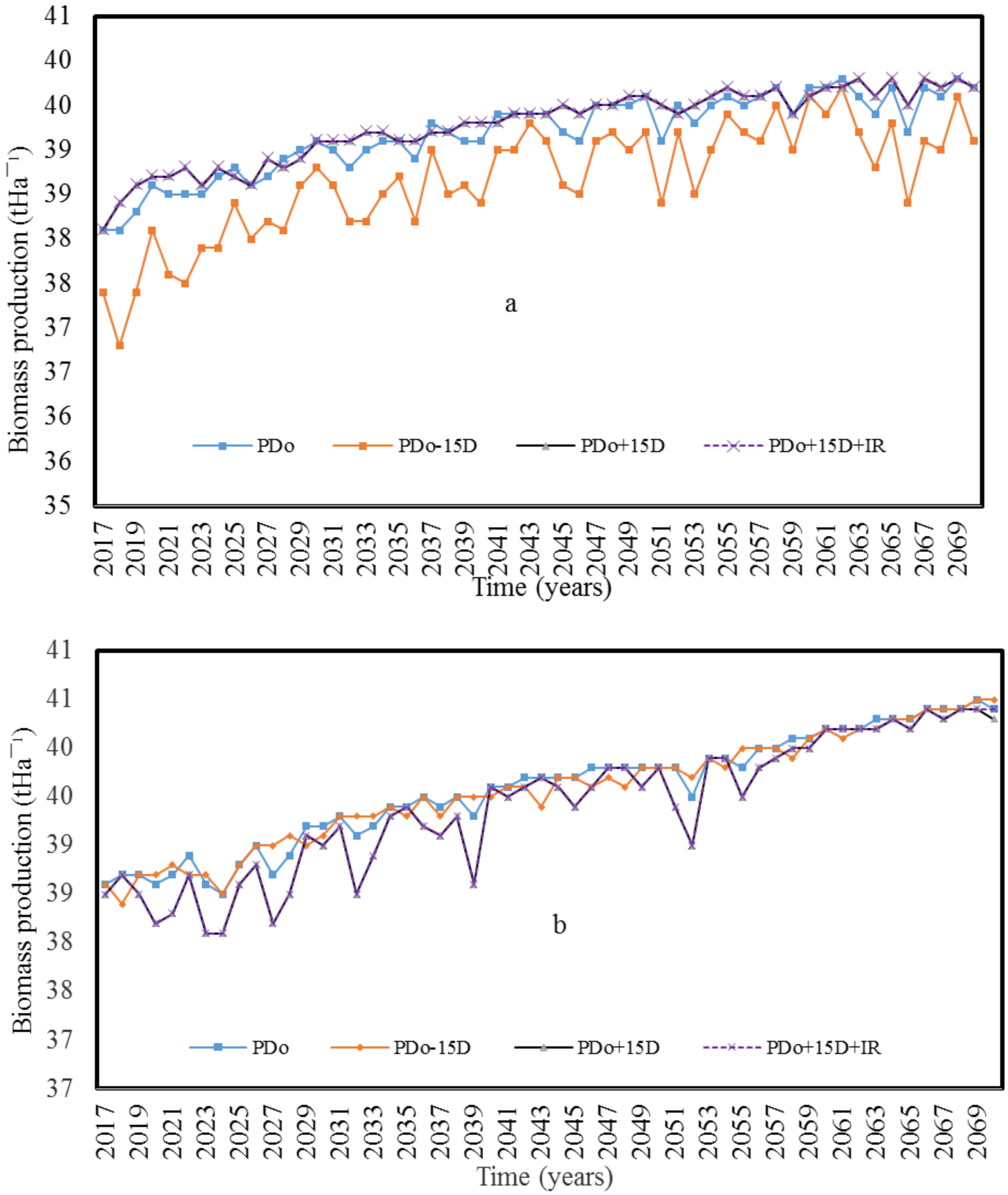


Figure 4.16: Projected sorghum (Muyira-1) biomass yield under RCP4.5 (a) and RCP8.5 (b) for MPI_M_MPI_ESM_LR climate model (PD_o = reference sowing date (baseline), PD_o-15D = 15 days before the baseline, PD_o+15D = 15 days after the baseline, PD_o-15D +IR = 15 days after the baseline with supplementary irrigation.

4.3.2.2. Maize (BH661)

With the exception of MPI_M_MPI_ESM_LR climate model, the projected biomass yield by all the other climate models and MME followed similar trend for the adaption options considered (Figures 4.17-4.21). Alteration of the planting time has sound effects on biomass yield of maize across the climate models considered. Under RCP4.5, CNRM_CERFACS_CNRM_CM5 and MME climate models projected lower biomass yield for early planting (PDo-15) during the two time slices. Similarly, ICHEC-EC-Earth model projected lower biomass yield in the Near-century compared with the reference sowing date. The overall reduction of biomass yield for PDo-15D ranged from 0.11 to 1.52 t ha^{-1} (Appendix Tables 4.18-4.27). On the contrary, under RCP4.5 and the two time slices, MOHC-HadGEM2-ES and MPI-M-MPI-ESM-LR models projected a higher biomass yield (0.01 to 1.34 t ha^{-1}) if early planting (PD0-15D) is adopted. For the same RCP and Mid-Century, the ICHEC-EC-Earth model projected higher biomass yield if planting is done 15 days earlier than the reference planting date.

In general, under given RCP and time slice, the climate models projected that delaying planting by 15 days (PDo+15D) will result in higher biomass yield reduction than early planting (PDo-15D). On the other hand, model projections of maize biomass yield varied with the type of climate model, RCPs, and time slices. Accordingly, under RCP4.5, ICHEC-EC-Earth (Near- and Mid-Centuries), CNRM_CERFACS_CNRM_CM5 (Near-Century), and MOHC-HadGEM2-ES (Mid-Century) models projected a reduction in biomass yield of maize by 0.31 to 2.28 t ha^{-1} if planting is delayed by 15 days than the reference planting date. Contrary to this, projection outputs of MPI-M-MPI-ESM-LR (both time slices), MOHC-HadGEM2-ES (Near-Century), and CNRM_CERFACS_CNRM_CM5 (Mid-Century) models revealed that delaying planting by 15 days could increase maize biomass yield by 0.12 to 1.61 t ha^{-1} as compared to the reference planting date.

On the other hand, with the exception of Near-centuries of MOHC-HadGEM2-ES and MPI-M-MPI-ESM-LR climate models, all the other models and time slices projected higher biomass yield (1.95 to 22.3 t ha^{-1}) compared to the reference planting date in both the Near- and Mid-centuries under RCP4.5. From the above discussion, it would be possible to conclude that earlier planting is better than late planting and late planting with supplementary irrigation is much better than all the other adaptation options for higher biomass yield of late-maturing maize variety.

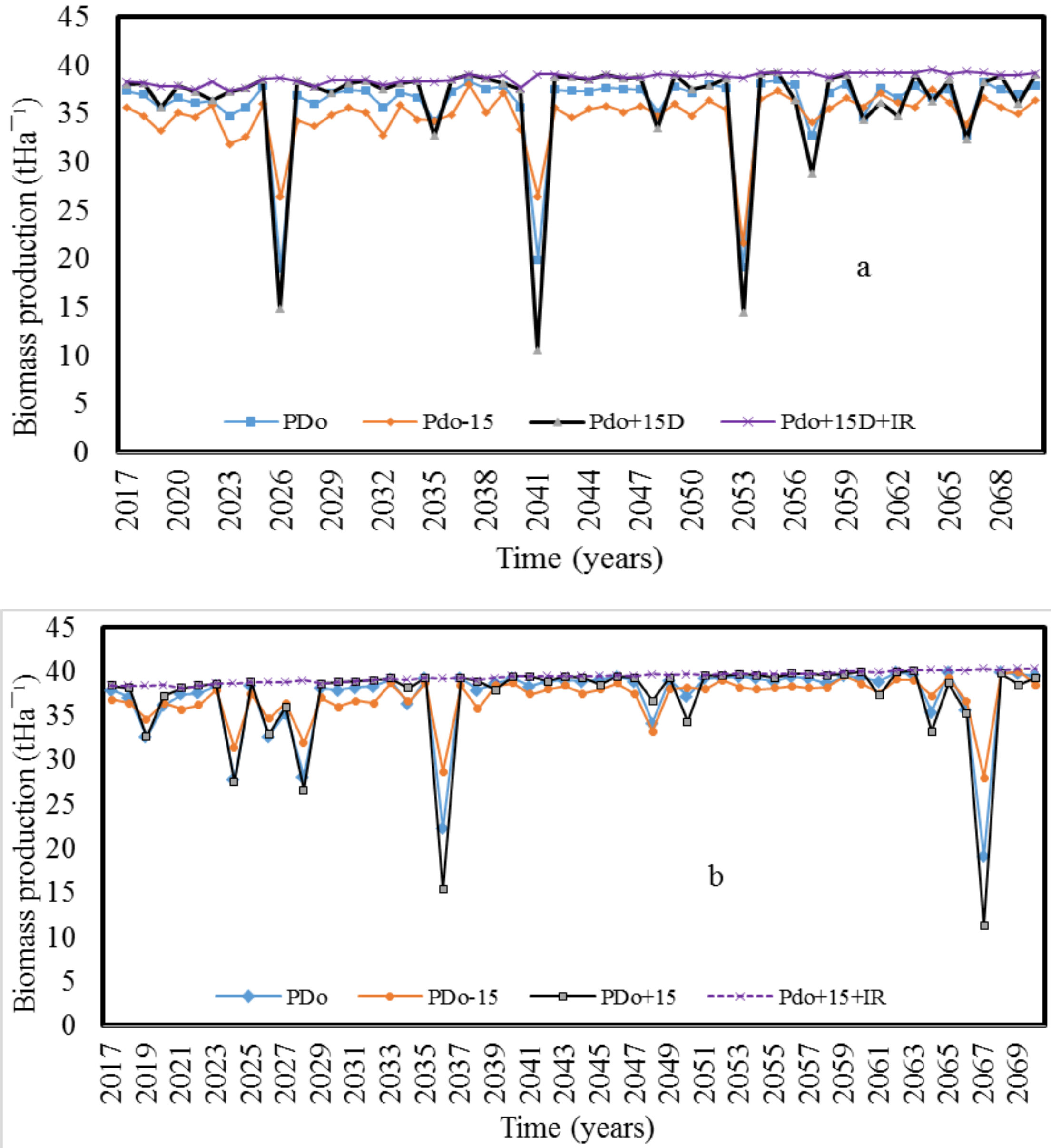


Figure 4.17: Projected maize (BH661) biomass yield under RCP4.5 (a) and RCP8.5 (b) for CNRM_CERFACS_CNRM_CM5 climate model (PD_o = reference sowing date (baseline), PD_o-15D = 15 days before the baseline, PD_o+15D = 15 days after the baseline, PD_o-15D +IR = 15 days after the baseline with supplementary irrigation.

Under RCP8.5 scenario there were no big differences exhibited in increment and reduction of projected maize biomass yield between PDo-15D and PDO+15D. However, with the exception of the Near-century of MPI-M-MPI-ESM-LR climate model, all the other models projected higher biomass yield (0.86 to 23.11 t ha^{-1}) compared with the other adaptation options (Appendix Tables 4.18-4.27).

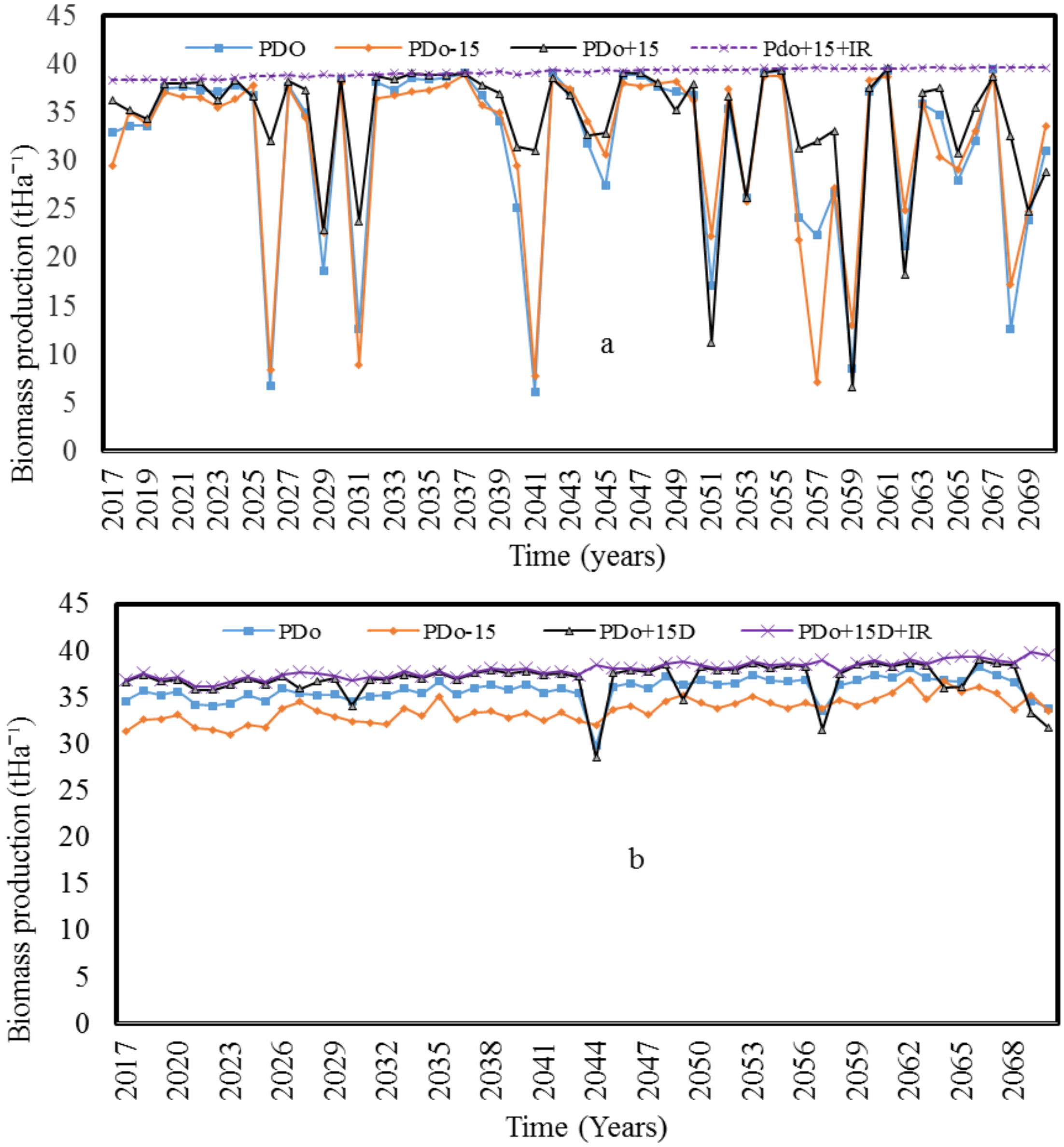


Figure 4.18: Projected maize (BH661) biomass yield under RCP4.5 (a) and RCP8.5 (b) for ICHEC-EC-Earth climate model (PD_o = reference sowing date (baseline), PD_o-15D = 15 days before the baseline, PD_o+15D = 15 days after the baseline, PD_o-15D +IR = 15 days after the baseline with supplementary irrigation.

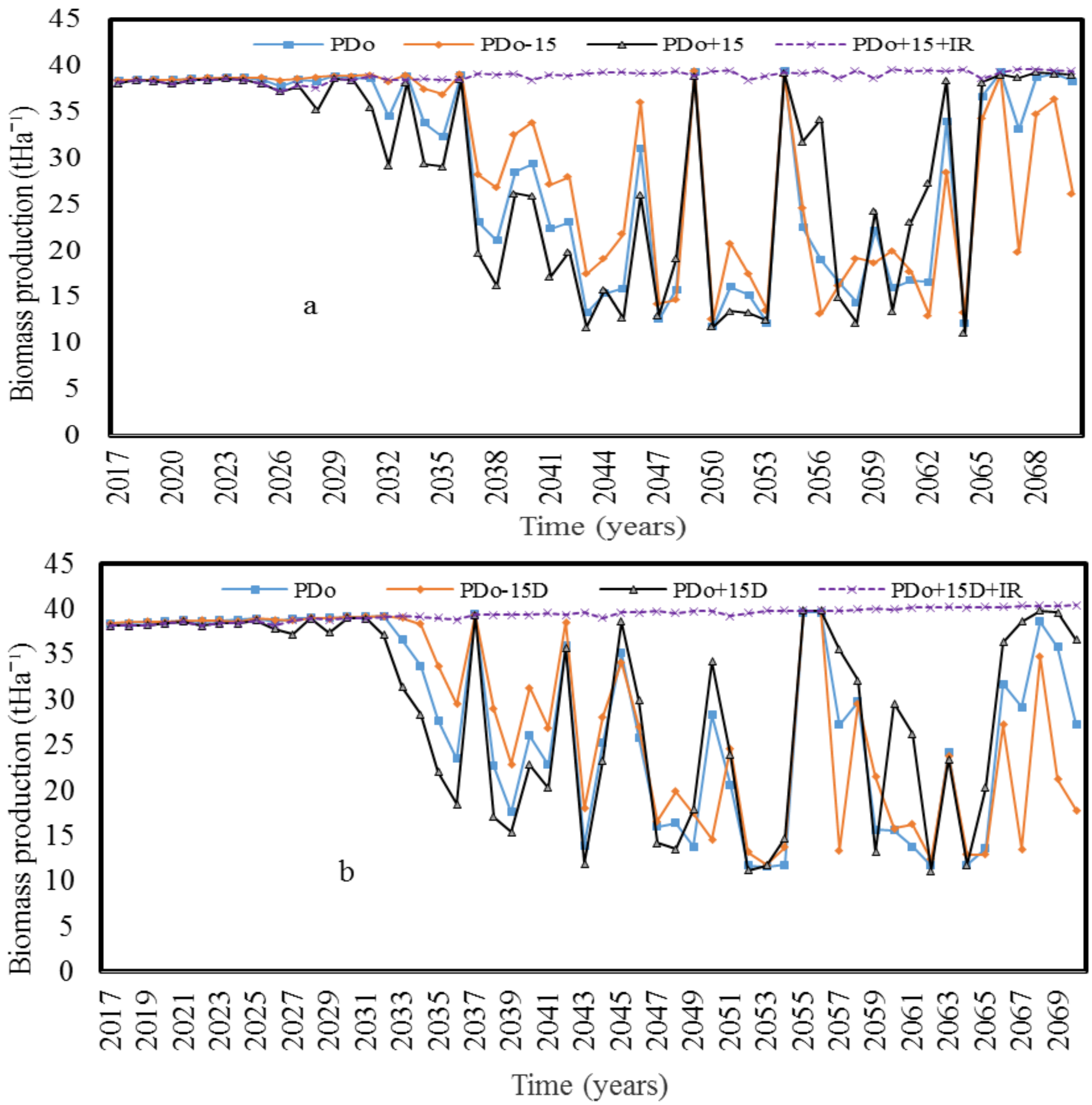


Figure 4.19: Projected maize (BH661) biomass yield under RCP4.5 (a) and RCP8.5 (b) for MOHC_HadGem2_ES climate model (PD_o = reference sowing date (baseline), PD_o-15D = 15 days before the baseline, PD_o+15D = 15 days after the baseline, PD_o-15D +IR = 15 days after the baseline with supplementary irrigation.

With regard to time slice, the models responded differently. Even within the same model, the projected biomass yield followed different trends under the Near- and Mid-Centuries. Some models predicted increase in biomass yield in the Mid-century as compared to Near-century.

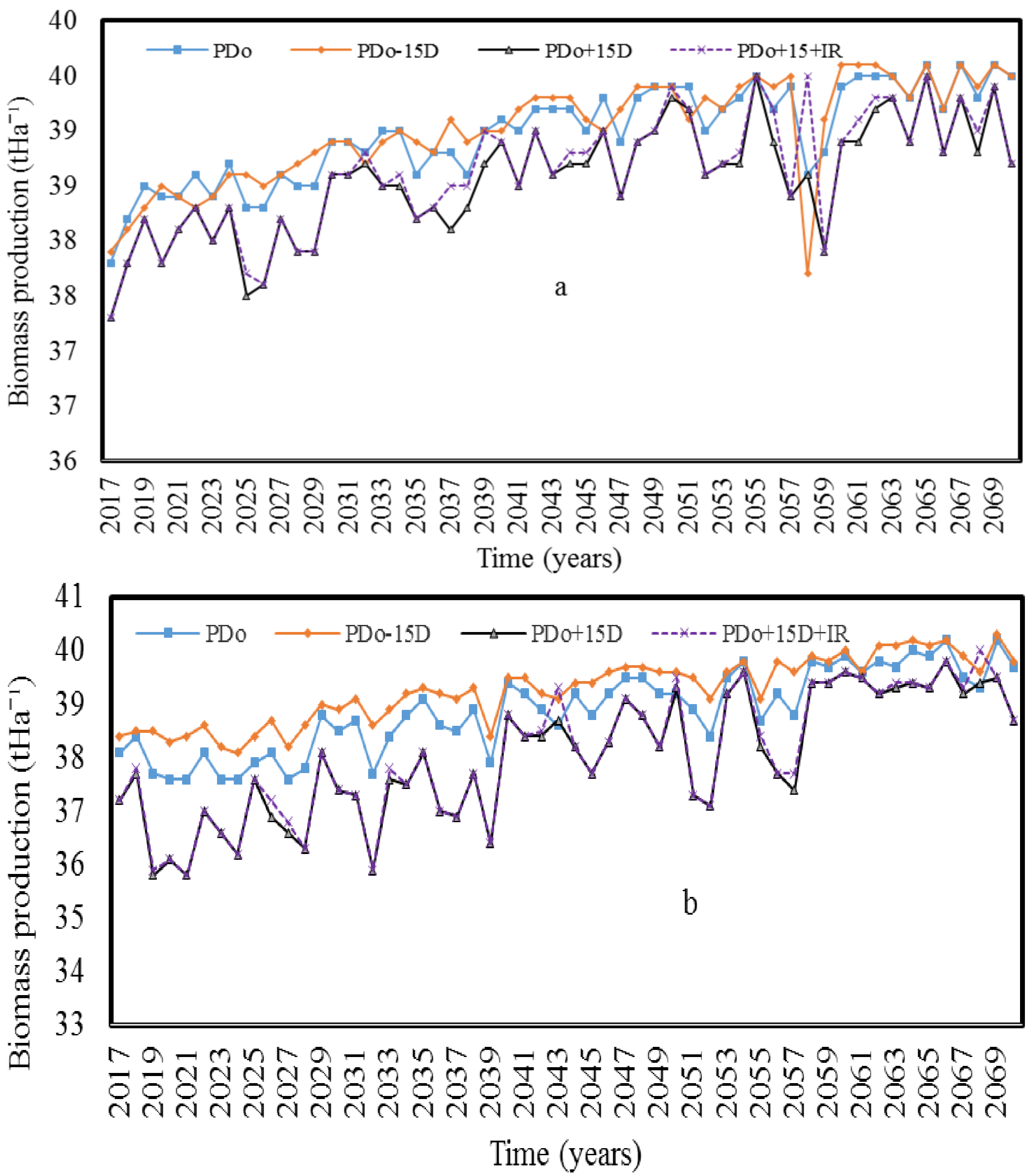


Figure 4.20: Projected maize (BH661) biomass yield under RCP4.5 (a) and RCP8.5 (b) for MPI_M_MPI_ESM_LR climate model (PD_o = reference sowing date (baseline), PD_o-15D = 15 days before the baseline, PD_o+15D = 15 days after the baseline, PD_o-15D +IR = 15 days after the baseline with supplementary irrigation.

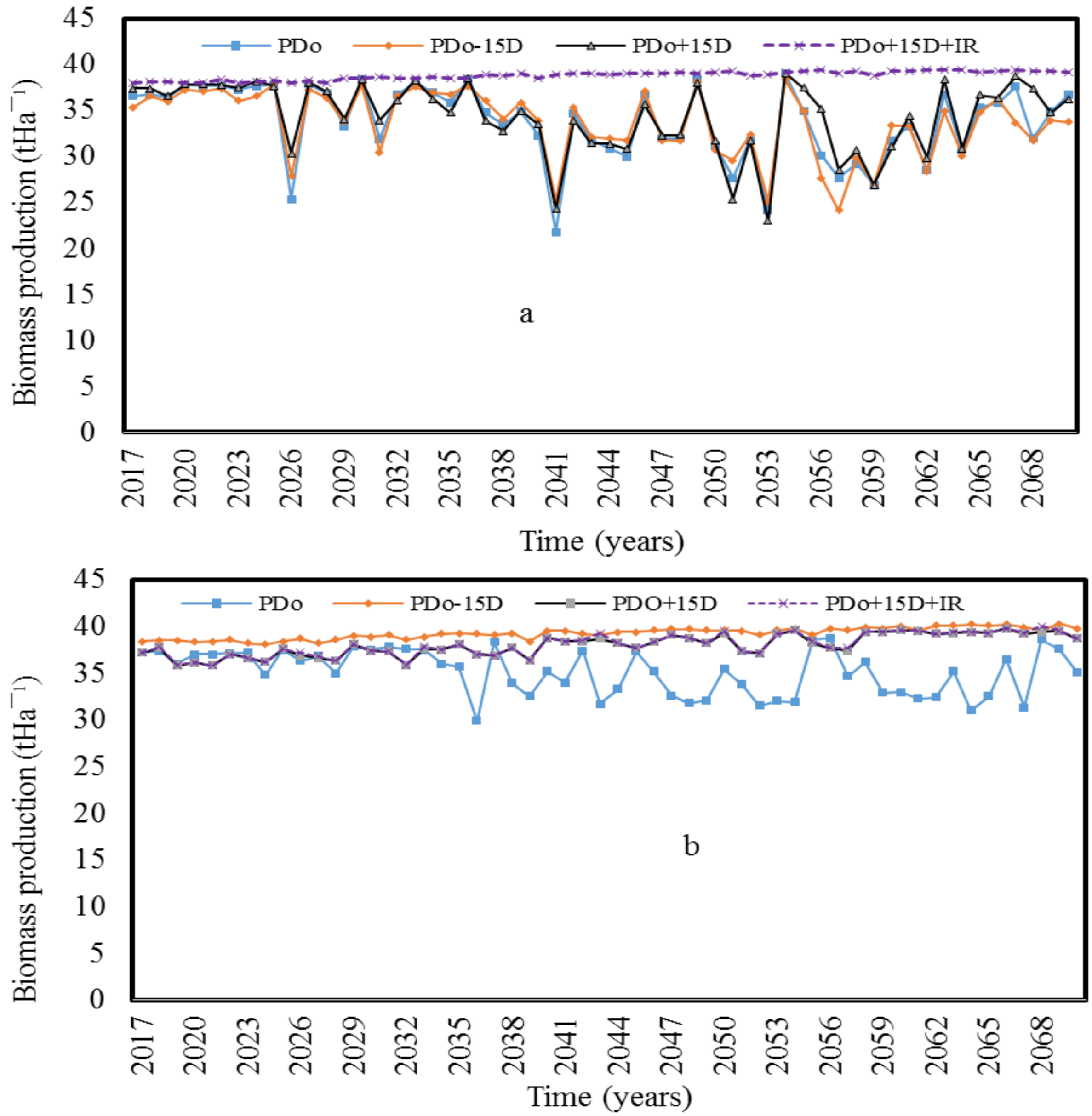


Figure 4.21: Projected maize (BH661) biomass yield under RCP4.5 (a) and RCP8.5 (b) for Multi Model Ensemble climate model (PD_o = reference sowing date (baseline), PD_o-15D = 15 days before the baseline, PD_o+15D = 15 days after the baseline, PD_o-15D +IR = 15 days after the baseline with supplementary irrigation.

4.3.3. Projected biomass carbon and its CO_2 equivalent for sorghum and maize

4.3.3.1. Sorghum (Muyira-1)

Biomass carbon and CO_2 equivalent were calculated for the two crops, under two emission scenarios, two time slots, and five climate models (Table 4.11). The results of projections by all models under RCP4.5 and the two time slots reveal that late planting alone and late planting with supplementary irrigation would result in higher biomass carbon (2.20 t ha^{-1}) and CO_2 equivalent (8.01 t ha^{-1}) than the reference planting date. On the other hand, all model projections gave lower biomass carbon (1.83 t ha^{-1}) and CO_2 equivalent (6.73 t ha^{-1}) for early planting under RCP4.5 and Near- and Mid-Centuries. Furthermore, slightly higher biomass carbon and CO_2 equivalent were projected for the Mid-Century than the Near-Century time slice across the climate models and adaptation options.

Under RCP8.5, the models projected different trends of biomass carbon and CO_2 equivalent across adaptation measures and time slots. MOHC-HadGEM2-ES climate model projected that implementing the three adaptation measures (PDo, PDo+15D, and PDO+15D+IR) during the Mid-Century could produce the highest biomass carbon (2.37 t ha^{-1}) and CO_2 equivalent (8.7 t ha^{-1}). Contrary to this, all the models projected lower biomass carbon and CO_2 equivalent for early planting than the reference planting date, with the lowest sorghum biomass carbon (1.67 t ha^{-1}) and CO_2 equivalent (6.13 t ha^{-1}) projected by ICHEC-EC-Earth climate model. Comparing the two RCPs and time slots, sorghum biomass carbon showed progressive reduction from RCP4.5 and RCP8.5 Mid-Centuries to RCP4.5 and 8.5 Near-Centuries. Also, it was noted that biomass carbon and CO_2 equivalent projection did not show a different response to supplementary irrigation compared with delayed planting date by 15 days.

Table 4.11: Projected mean organic carbon and CO_2 equivalent of sorghum (Muyira-1) (t ha^{-1}) for selected adaptation measures under RCP4.5 and 8.5, and Near- and Mid-Centuries

Model	RCP	Time slice	Parameter	Adaptation measures			
				PDo	PDO-15D	Pdo+15D	PDO+15D+IRR
CNRM-CERFACS-CNRM-CM5	4.5	NC	Organic carbon	2.04	1.83	2.20	2.20
			CO_2 equivalent	7.48	6.72	8.01	8.07
		MC	Organic carbon	2.04	1.83	2.20	2.20
			CO_2 equivalent	7.48	6.72	8.01	8.07
	8.5	NC	Organic carbon	2.21	2.06	2.29	2.29
			CO_2 equivalent	8.09	7.56	8.41	8.41
		MC	Organic carbon	2.21	2.06	2.29	2.29
			CO_2 equivalent	8.09	7.56	8.41	8.41
ICHEC-EC-Earth	4.5	NC	Organic carbon	2.04	1.67	2.20	2.20
			CO_2 equivalent	7.48	6.13	8.07	8.07
		MC	Organic carbon	2.04	1.83	2.20	2.20
			CO_2 equivalent	7.48	6.73	8.07	8.07
	8.5	NC	Organic carbon	2.21	2.06	2.29	2.29
			CO_2 equivalent	8.09	7.56	8.41	8.41
		MC	Organic carbon	2.21	2.06	2.29	2.29
			CO_2 equivalent	8.09	7.56	8.41	8.41
MOHC-HadGEM2-ES	4.5	NC	Organic carbon	2.04	1.83	2.20	2.20
			CO_2 equivalent	7.48	6.73	8.07	8.07
		MC	Organic carbon	2.04	1.83	2.20	2.20
			CO_2 equivalent	7.48	6.73	8.07	8.07
	8.5	NC	Organic carbon	2.21	2.06	2.29	2.29
			CO_2 equivalent	8.09	7.56	8.41	8.41
		MC	Organic carbon	2.39	2.06	2.39	2.39
			CO_2 equivalent	8.7	7.56	8.7	8.7
MPI-M-MPI-ESM-LR	4.5	NC	Organic carbon	2.04	1.83	2.20	2.20
			CO_2 equivalent	7.48	6.73	8.07	8.07
		MC	Organic carbon	2.04	1.83	2.20	2.20
			CO_2 equivalent	7.48	6.73	8.07	8.07
	8.5	NC	Organic carbon	2.21	2.06	2.29	2.29
			CO_2 equivalent	8.09	7.56	8.41	8.41
		MC	Organic carbon	2.21	2.06	2.29	2.29
			CO_2 equivalent	8.09	7.56	8.41	8.41

4.3.3.2 Maize (BH661)

Under RCP4.5, all the climate models projected slightly lower biomass carbon and CO_2 equivalent for early planting than the reference planting date during the Mid- and Near-Centuries (Table 4.12). Similarly, all the models projected that a higher biomass carbon and CO_2 equivalent could be obtained if late planting alone and late planting plus supplementary irrigation are used instead of the reference planting or early planting. Across models and time slots, late planting combined with supplementary irrigation would result in higher biomass carbon and CO_2 equivalent than late planting alone. This suggests that maize will respond well to supplementary irrigation under changed future climate. The percentage deviation between PDo and PDo+15D+IR ranged from 5.7 to 6.1%. Except in very few instances, the projections of all the models suggest that biomass carbon and CO_2 equivalent would remain about the same during the Mid- and Near Centuries.

Under RCP8.5, the models projected slightly different patterns than RCP4.5 in terms of biomass carbon production by the adaptation measures. Accordingly, except MOHC-HadGEM2-ES model, all the other models' projections revealed that slightly higher biomass carbon yield and CO_2 equivalent will be obtained from adopting earlier (PD_o-15) and late planting (PD_o+15) than the reference planting date (PD_o) during both time slots. Furthermore, the models projected that a consistently higher biomass carbon yield and CO_2 equivalent than all the other adaptation measures will be obtained if late planting is combined with supplementary irrigation in the coming 50 years. In addition, all the models projected the same amount of biomass carbon and CO_2 equivalent for early and late planting during the Mid- and Near-Centuries. Except MOHC-HadGEM2-ES model, all models projected the same biomass carbon for NC and MC under reference planting and early planting dates. For late planting alone, across models and adaptation measures, the same amount of biomass carbon is projected for Near- and Mid-Centuries. This holds true for late planting plus supplementary irrigation with the exception of MPI-M-MPI-ESM-LR model.

The results of the study depicted that biomass carbon production projected by a given model for a given adaptation measure might vary depending on the types of RCPs considered. To this effect, under the reference and late planting dates, the biomass carbon projected is relatively higher under RCP4.5 than RCP8.5 during Near- and Mid-Centuries. On the contrary, under early planting, the biomass carbon under RCP8.5 will be relatively higher than that of RCP4.5 during both time slots. Under late planting plus irrigation, the effect of RCPs is not consistent. Numerically, early planting will reduce biomass carbon of the reference planting date by 4.17 to 4.19% (both under RCP4.5) and improve it by 0.47% (RCP8.5). Similarly, late planting alone will improve the biomass carbon of the reference planting date by 0.47 (RCP8.5) to 2.33% (RCP4.5 and MC). Relatively higher improvement in biomass carbon of the reference planting comes from the use of late planting and supplementary irrigation. This adaptation measure resulted in 6.02 (RCP4.5) to 8.33% (RCP8.5) biomass carbon improvement as compared to the reference planting date.

Table 4.12: Projected mean organic carbon and CO_2 equivalent of maize (BH 661) (t ha^{-1}) for selected adaptation measures under RCP4.5 and RCP8.5

Model	RCP	Time slice	Parameter	Adaptation measures			
				PDo	PDO-15D	Pdo+15D	PDO+15D+IRR
CNRM-CERFACS-CNRM-CM5	4.5	NC	Organic carbon	2.16	2.07	2.20	2.29
			CO_2 equivalent	7.90	7.58	8.07	8.42
		MC	Organic carbon	2.16	2.07	2.20	2.29
			CO_2 equivalent	7.90	7.58	8.07	8.42
	8.5	NC	Organic carbon	2.15	2.16	2.16	2.33
			CO_2 equivalent	7.89	7.91	7.91	8.54
		MC	Organic carbon	2.15	2.16	2.16	2.33
			CO_2 equivalent	7.89	7.91	7.91	8.54
ICHEC-EC-Earth	4.5	NC	Organic carbon	2.16	2.07	2.20	2.29
			CO_2 equivalent	7.90	7.58	8.07	8.42
		MC	Organic carbon	2.15	2.07	2.20	2.29
			CO_2 equivalent	7.90	7.58	8.07	8.42
	8.5	NC	Organic carbon	2.15	2.16	2.16	2.30
			CO_2 equivalent	7.89	7.91	7.91	8.54
		MC	Organic carbon	2.15	2.16	2.16	2.30
			CO_2 equivalent	7.89	7.91	7.91	8.54
MOHC-HadGEM2-ES	4.5	NC	Organic carbon	2.16	2.07	2.20	2.33
			CO_2 equivalent	7.90	7.58	8.07	8.53
		MC	Organic carbon	2.16	2.07	2.20	2.29
			CO_2 equivalent	7.90	7.58	8.07	8.42
	8.5	NC	Organic carbon	2.16	2.16	2.16	2.30
			CO_2 equivalent	7.89	7.91	7.91	8.54
		MC	Organic carbon	2.15	2.06	2.16	2.30
			CO_2 equivalent	7.89	7.55	7.91	8.54
MPI-M-MPI-ESM-LR	4.5	NC	Organic carbon	2.16	2.07	2.20	2.29
			CO_2 equivalent	7.90	7.58	8.07	8.42
		MC	Organic carbon	2.16	2.07	2.20	2.29
			CO_2 equivalent	7.90	7.58	8.07	8.42
	8.5	NC	Organic carbon	2.15	2.16	2.16	2.30
			CO_2 equivalent	7.89	7.91	7.91	8.54
		MC	Organic carbon	2.15	2.16	2.16	2.33
			CO_2 equivalent	7.89	7.91	7.91	8.54

CHAPTER FIVE

DISCUSSION

5.1. Soil Carbon Stock under Different Land Uses

As pointed out by the World Bank (2012), soils, by acting as an interface between vegetation, oceans, and atmosphere, determine the global carbon dynamics. The same source indicated that the soil carbon pool (2.500×10^{12} t up to a 2-m depth) is more than three times the size of the atmospheric pool (7.60×10^{11} t) and about 4.5 times the size of the biotic pool (5.60×10^{11} t). This indicates that soil can be a huge sink or source for greenhouse gases depending on how it is used or managed. The soil's potential to sequester carbon is mainly dependent on pedological factors, such as soil texture and clay mineralogy, depth, bulk density, aeration, and proportion of coarse fragments (Sollins *et al*., 1996; Baldock and Skjemstad, 2000; World Bank, 2012). In evaluating soil as a sink or emitter of greenhouse gases, therefore, it is important to characterize it in terms of its salient attributes, such as physical, chemical, and biological properties (Ehrenbergerová *et al*., 2016). In view of this, soils under the four current land uses of the study area were characterized in terms of their selected properties.

5.1.1. Soil physical properties

The soils under the natural forest had a lower bulk density value as compared to those under other land uses. This might be attributed to the relatively higher organic matter content under the forestland. In line with this, Nahusenay *et al*. (2014) revealed presence of inverse relationship between organic matter and bulk density. Teshome *et al*. (2013) and Tassew (2017) reported significantly lower bulk density values in the natural forest as compared to grazing and cultivated lands in western and central highlands of Ethiopia, respectively. In all the land uses, bulk density increased down the soil depth. The increase in soil bulk density with soil depth might be associated with decline in organic matter, less aggregation, and root penetration in addition to the expected compacting effect of the overlying soil mass. Similar studies conducted in Ethiopia reported a general increase in bulk density value with soil depth (Nahusenay *et al*., 2014; Samuel, 2017). The bulk density values of the soils under the four land use types are not likely to restrict plant growth because of excessive compaction (Jones, 1983).

In terms of particle size distribution, significantly higher sand content was recorded in soils under the forestland as compared to the other land use types. This is probably due to the steep slope and high elevation of the forestland, where removal of finer particles by water erosion is high. In consent with this finding, Nahusenay and Kibebew (2015) and Amanuel *et al*. (2018) reported significantly higher sand content in soils under natural forest as compared to shrub, grazing, and cultivated lands. Presence of high clay content at the 0-20 cm soil depth of the cultivated and grazing lands than the forestland indicates the selective removal of the finer particles, such as silt and clay, by water erosion from the steep slopes and their subsequent accumulation in the gently sloping and low-lying parts of the study area. Ellerbrck and Gerke (2013) pointed out that during erosion clay particles can be transported along hill slopes from hilltops to foot-slope areas and form colluvic soil at the topographic depressions. In consent with the findings of the current study, Yimer *et al*. (2007) reported accumulation of clay particles at lower soil depths.

The World Bank (2012) highlighted the importance of soil properties, particularly soil texture, in soil carbon sequestration. In general, soil carbon sequestration rate increases with clay content. In view of this, soils of the grazing and cropland have good clay content, which implies the presence of high potential for sequestering carbon in these soils. Through their good nutrient and water holding capacity, these soils can potentially support good vegetation growth for biomass production. Good biomass production means good organic matter input into the soil if it is not used for some other purposes that physically remove the biomass from the soil. In agreement with this, Dlamini *et al*. (2014) indicated that fine-textured soil stores more plant-available water, retains more nutrients, and provides better soil structure for plant growth, and consequently, has more plant C input than coarse-textured soil. On the contrary, organic matter decomposes faster in a coarse-textured soil, because it lacks the protection generally afforded by an abundance of clay particles (Chan *et al*., 2010).

5.1.2. Soil chemical properties

As compared to the other land use types, lower pH (H_2O) value was recorded in soils under cropland. This could be attributed to depletion of basic cations through crop harvest and continuous use of acid-forming fertilizers, such as di-ammonium phosphate $(NH_4)_2HPO_4$), which produces strong acids when oxidized by soil microbes (Nega and Heluf, 2013). For the last many years (over 50 years), the two types of fertilizers that have been in use throughout the country were urea and DAP (Di-ammonium phosphate). The relatively higher pH values recorded at the bottom layers (40-60 cm) in some of the land uses could be related to the leaching of basic cations from the upper layers and subsequent deposition at the lower soil depths (Soto and Diazfierroz, 1993). Following soil pH rating suggested by Tekalign (1991), the pH values of the studied soils fall within the range of slightly acidic in the cropland to neutral in the other land use types. The pH values recorded in soils under the four land uses are within the range that is considered favorable for availability of most plant nutrients, growth of plants, and activity of microorganisms (Landon, 2014). This implies that soils under the different land uses do not have limitations due to their pH and, hence, can support good growth of plants and activity of microorganisms, all of which are important for good biomass production.

The highest total nitrogen content was recorded in soils of the natural forestland. This could be due to the higher organic carbon content in the natural forestland, which is the major source of total nitrogen (essentially organic nitrogen) (Landon, 2014). This is also supported by the highly significant ($P < 0.01$) and positive correlation ($r = 0.96$) between total nitrogen and organic carbon content. On the other hand, the low total nitrogen content in soils of the cropland could be associated with complete removal of crop residues, which results in addition of low organic matter to the soil. Loss of considerable total nitrogen following conversion of land from forest to cropland was reported in many similar studies conducted elsewhere (Lemenih *et al*., 2005; Eyayu *et al*., 2009; Taye, 2011; Mojiri *et al*., 2012; Teshome *et al*., 2013; Guillaume *et al*., 2015; Nahusenay and Kibebew, 2015). A study conducted by Xue and An (2018) at a small watershed on the Loess Plateau in China reported a higher content of SOC and total N in shrub land and natural grassland areas as compared to other land uses (farmland, orchard, abandoned farmland, man-made grassland). The same study reported the lowest concentration under cropland.

Following general total nitrogen rating proposed by Landon (2014), the total nitrogen content of the soils falls within the range of high in natural forest, medium in coffee agroforestry and grazing lands, and low in crop lands. Unless addressed through appropriate nutrient management intervention, the low nitrogen content in soils of the cropland can reduce biomass production and carbon sequestration potential. de Vries *et al*. (2009) explained that high N deposition on forest ecosystems might enhance C sequestration via increased growth and increased accumulation of soil organic matter through increased litter production and/or increased recalcitrance of N-enriched litter, leading to reduced long-term decomposition rates of organic matter.

The soil C:N ratio has been used as an indicator of important soil attributes, such as soil microorganism community structure and changes in soil quality in terrestrial ecosystems (Hogberg *et al*., 2007; Tang *et al*., 2007). Aber (1992, cited in Xue and An, 2018) showed the significant effect of C:N ratio on important biochemical processes, such as soil nitrogen mineralization, fixation, and nitrification.

In this study, some of the C:N ratios were outside the range that is considered normal (10-12) for arable mineral soils. As indicated by Hazelton and Murphy (2007), ratios between 15:1 and 25:1 indicate a slowing in the decomposition process due to scarcity of nitrogen. Accordingly, the ratios recorded in some surface and subsurface layers of the cultivated, grazing, and coffee agroforestry lands indicate the presence of slow decomposition process probably due to the presence of resistant structures and organic compounds. Strong and Mason (1999) pointed out that organic matter with a high C:N ratio (> 20) locks up nitrogen as it decomposes, decreasing available nitrogen for the crop, which in turn could negatively affect biomass production and eventually carbon sequestration in soils. In line with this, Zhou *et al*. (2019) reported that low litter carbon-to-nitrogen ratio (C/N) promoted SOC accumulation. However, Tong *et al*. (2009) reported that the SOC and total N accumulation are not synchronous. The differences in soil C:N ratios among the land use types could reflect differences in the accumulation rate of SOC and total N (O'Brien *et al*., 2010).

5.1.3. Soil carbon stock under different land use/land cover types

Recent studies (e.g., Tubiello *et al*., 2013; Tubiello *et al*., 2015; IPCC, 2018) indicated that AFOLU accounts for up to 30% of the total anthropogenic greenhouse gas emissions. These emissions come from crop and livestock production, forestry, and associated land use changes. However, Tubiello *et al*. (2013) pointed out that the global efforts to report emissions from AFOLU, as compared to those for fossil fuel emissions, are very much limited. On the other hand, many reports (e.g., Houghton and Hackler , 2012, cited in Tubiello *et al*., 2013) emphasized that the presence of scientifically improved estimates of anthropogenic forcing and its trend evolution are needed to more reliably predict medium to long-term climatic effects and to determine feasible mitigation strategies. Assessing carbon stock of different land uses at a watershed level will contribute to the global carbon database and provide empirical evidence to decision makers. This will enable decision makers to make rational land use decisions that take adaptation to and mitigation of climate change into consideration.

Results of the current study indicate that, in all land uses, about 38-40% of the SOC was stored in the 0-20 cm soil layer, while about 60-68% was recorded in the 20-60 cm soil depth, indicating the importance of the deeper soil layers in storing carbon. In the natural forest and coffee agroforestry, respectively, about 68 and 92% of their total carbon stock was found in the soil, which again implies that, even under vegetation covered ecosystems, significant amount of the carbon stock is stored within the soil system. Similarly, Abyot *et al*., (2019) reported that the highest percentage of carbon was stored in soil organic carbon pool in Gerba Dima moist Afromontane forest, south western Ethiopia. Global estimates of soil organic carbon for different time periods were also provided in many reports of recent studies (Köchy *et al*., 2015; Batjes, 2016; Lal, 2016; Sanderman *et al*., 2017). The soil carbon stock in the crop and grasslands was very low as compared to the coffee agroforestry and natural forest. The soil carbon stock under the natural forest was 1.72 times that in the cropland. This low carbon stock under the cropland could be due to the exploitative nature of the farming system in the study area, which does not leave any residue on the soil or add enough organic matter to the soil. Furthermore, the frequent tillage practiced by farmers might have resulted in fast decomposition of the small amount of organic matter in the soil, releasing CO_2 into the atmosphere. In Ethiopia, the FAOSTAT (2019) database indicates that around 1.80×10^5 t of CO_2 was emitted to the atmosphere through burning crop residues in the year 2017. This clearly indicates that the agricultural practices in the country are not climate-smart and, hence, emit significant amount of greenhouse gases to the atmosphere. Many studies have indicated loss of soil organic carbon when a land is converted from natural to managed ecosystem (IPCC, 2013; Yihenew and Getachew, 2013; Guillaume *et al*., 2015; Fan *et al*., 2016; Iqbal and Tiwari, 2016; Assefa *et al*., 2017; Kassa *et al*., 2017; Belay and Getaneh, 2018; Tebkew, 2018). Similarly, other studies have documented the gain in soil organic carbon when a land is converted from agricultural land to vegetated land (e.g., to forestland) (Priano *et al*., 2018; Stefano and Jacobson, 2018).

Absence of proper investment in soil quality improvement practices such as erosion control, water management, application of fertilizers (chemical and organic), and other amendments in subsistence agricultural practices is known to increase emission of greenhouse gases such as carbon dioxide, methane, and nitrous oxide, from agricultural ecosystems (World Bank, 2010, cited in World Bank, 2012). According to World Bank (2012), agricultural soils have lost more than 5.0×10^{10} t of carbon due mainly to mismanagement of the soils. Some of this lost carbon can be recaptured by adopting sustainable land management practices (World Bank, 2012). Available evidences indicate that sustainable land management could enhance carbon benefits through conservation of carbon itself, reduced emissions, and carbon sequestration (World Bank, 2012; IPCC, 2018). From the foregoing discussion, it can be inferred that implementation of tested and proven sustainable land management practices in the study area is very much needed to enhance carbon sequestration of the different land uses.

5.1.4. Aboveground carbon stock

The role of plants in general in the global carbon cycle as sources and emitters is well documented. Being major pools of carbon in the terrestrial ecosystem (FAO and ITPS, 2015), forests play an important role in mitigating climate change (IPCC, 2009; Sheikh *et al*., 2009). Through the process of deforestation and forest degradation, forests can also be emitters of significant amount of carbon dioxide (Federici *et al*., 2015). It is, therefore, important to know the amount of carbon stored in plants of a given area. For this study, aboveground carbon was measured under the natural forest and coffee agroforestry land use types only. The grass and croplands did not have any measurable aboveground biomass and, hence, aboveground carbon stock was not measured. The aboveground biomass carbon stock in the natural forest was higher than that in the coffee agroforestry due to the presence of many large trees and other vegetation cover. This indicates that presence of trees in a given environment ensures storage of biomass carbon in addition to its sequestration through the process of photosynthesis. This helps greatly in mitigating climate change. The large aboveground carbon stock density in the natural forest could be associated with the presence of higher density of trees with larger diameter at breast height (dbh) (Adugna *et al*., 2013; Hamere *et al*., 2015).

Similar to the current finding, Hamere *et al*. (2015) and Tibebu and Teshome (2015) reported high aboveground biomass carbon in Gedo and Adaba Dodola community forests, respectively.

In the study area, deforestation and forest degradation are very common. These processes might have emitted huge quantity of carbon in to the atmosphere. Global evidences show that deforestation and forest degradation are causing emission of large quantity of CO_2 from forestlands due to their conversion to other land uses (IPCC, 2007; Federici *et al*., 2015). FAO (2010) reported reduction in forest biomass due to conversion of forestlands to other land uses. Other similar studies reported that deforestation and inappropriate land-use practices are among the prime causes that reduce carbon sequestration potential of a given system through increasing CO_2 emission, which eventually results in global warming (van der Werf *et al*., 2009; IPCC, 2013; Cui *et al*., 2015). A study conducted about two decades ago indicated that the forest cover of Ethiopia reduced from about 35% at the turn of the century to 2.4% in 1992 (EPA, 1998). This loss of the forest cover must have resulted in emission of unprecedented quantity of CO_2 into the atmosphere. Yitebitu *et al*. (2010) underscored that, if the current deforestation rate continues, Ethiopia could lose the 2.76×10^9 t of aboveground carbon stored in its forest resources. Conserving forests is, therefore, mandatory in order to offset emission through forest degradation and deforestation.

Though it was small in quantity, the coffee agroforestry also contributed to carbon sequestration through its aboveground biomass. The relatively small amount of biomass carbon could be associated with the presence of limited shade trees and absence of understory growth. However, the importance of agroforestry in carbon sequestration and mitigation of climate change is well recognized (Schroth *et al*., 2002). In this highly populated area with very small land holding per capita, agroforestry has a high prospect because of its added advantages that include providing construction material and fuelwood (Rice and Ward, 2008), and reducing expansion of subsistent agriculture (Noponen *et al.*, 2013) by increasing agricultural production from a unit of land. Studies conducted in different parts of the world indicate that the amount of carbon stored in the biomass of coffee agroforestry depends on such factors as type of shade tree and number of plants per hectare (Ha¨ger, 2012; Schmitt-Harsh *et al*., 2012; Mesele *et al*., 2013; Ehrenbergerová *et al*., 2016).

5.1.5. Root carbon stock

In an environment with vegetation cover, roots are important sources of soil organic carbon (Strand *et al*., 2008). Supply of carbon to soil through the process of rhizodeposition, for instance, is another source of organic carbon (Rees *et al*., 2005; Weintraub *et al*., 2007). The result obtained in this study (23.29 t ha $^{-1}$) was lower as compared with what is reported in other findings in Ethiopia (Tulu *et al*., 2011; Adugna *et al*., 2013; Mohammed *et al*., 2014; Hamere *et al*., 2015; Muluken *et al*., 2015; Abyot *et al*., 2019). The lower carbon stock in this study could be the result of lower aboveground biomass since the root carbon stock was estimated from the aboveground biomass. Comparatively, however, the root carbon stock in the natural forestland was higher than that in the coffee agroforestry, implying that forests could be better in storing carbon in their deep root system. In line with this, Cairns *et al*. (1997) and Hirte *et al*. (2017) indicated that trees with deep root systems can store substantial amount of carbon in their root biomass though this is expected to decrease with soil depth. Haile *et al*. (2010) claimed that tree based systems have a greater potential to sequester C into more stable stocks in deeper soil than some treeless systems. Nevertheless, Noponen *et al*. (2013) argues that this contribution is strongly influenced by other site- and land use change-specific variables. Furthermore, the status of the forest and its species composition along with climatic and edaphic factors could create differences in root carbon stock among forests. Given the importance of root carbon stock in sequestering organic carbon and mitigating climate change across the globe, a number of studies have been made on root carbon stock of different vegetation covers, including agroforestry systems, providing different estimates of root biomass carbon (Ordonez *et al*., 2008; Ullah and Amin, 2012; Mesele *et al*., 2013; Abyot *et al*., 2019). In the study area where the aboveground biomass is subject to different removal processes, the root can be seen as a very good venue where carbon could be sequestered. Therefore, accurate assessment of the root carbon stock using direct instead of the indirect methods should be followed, to get better estimates of the root carbon stock.

5.1.6. Litter carbon stock

Litter is another important source of organic carbon, particularly in ecosystems covered with natural vegetation. As pointed out by Mafongoya *et al*. (1998) and Lemma *et al*. (2007), supply of carbon into the soil depends on litter decomposition rate, which in turn is influenced by litter quality and plant species diversity. In this study, the litter carbon stock recorded under the natural forest and agroforestry land use types was low as compared to that recorded in tropical dry forests (Brown and Lugo, 1982; Brown, 1997;) and other forests in Ethiopia (Tulu *et al*., 2011; Adugna *et al*., 2013; Muluken *et al*., 2015; Abyot *et al*., 2019). The lower litter carbon in the study area could be associated with the presence of few and less divers trees in the forest. Furthermore, the community collects litter particularly twigs and branches for fuel wood. However, the current study yielded higher litter C compared with Montane forests of Central Mexico (Ordo´n˜ez *et al*., 2008). On the other hand, the coffee agroforestry yielded 0.36±0.06 t C ha^{-1}, which is less than the findings of Ha¨ger (2012) and Hergoulac´h *et al*. (2012). The lower litter carbon in coffee agroforestry might be due to the fact that the system has a single tree species as shade tree and coffee is intercropped with other crops in which the continuous disturbance of the soil through tillage hastens the rapid decomposition of the small amount of organic carbon. As indicated by Ordóñez *et al*. (2008), litter plays a very important role in the carbon biogeological cycle as the interface between carbon in vegetation and in soil. Hence, litter management is important to guarantee continuous flow of organic matter in the system. Many studies conducted across different parts of the world have quantified the contribution of litter carbon stock from different forest ecosystems (Brown and Lugo, 1982; Brown, 1997; Ordo´n˜ez *et al*., 2008; Tulu, 2011; Adugna, 2013; Mohammed *et al*., 2014; Muluken *et al*., 2015) and coffee agroforestry systems (Ha¨ger, 2012; Hergoulac´h *et al*., 2012; Mesele *et al*., 2013).

Tubiello *et al*. (2015) pinpointed that better information on AFOLU emissions is critical in many developing countries, given the potential to identify and fund actions that can usefully bridge national food security, resilience, mitigation, and development goals into one coherent package. Furthermore, the terms of the UN Framework Convention on Climate Change require that any improvements in soil carbon due to land-use changes and managed agroecosystems should be included in National Greenhouse Gas Inventories (IGBP, 1998). More recently, Le Quéré *et al*. (2018) assessed the global carbon budget and emphasized on the importance of accurate assessment of anthropogenic carbon dioxide (CO_2) emissions to better understand the global carbon cycle, support the development of climate policies, and project future climate change. In view of this, the current study provided reliable information on the status of carbon stock under the different land use types at Hades Sub-watershed. Due to the presence of degradation under all the identified land use types, the carbon stock was generally low. This calls for introduction of sustainable land management practices that are compatible with local context and the use of every parcel of land according to its suitability for a given use. The practices to be used and the uses of the land should ensure protection of the resources from any form of degradation, enhance productivity, and increase carbon stock and sequestration. The land use types should be identified through land suitability evaluation, which identifies the required interventions in terms of management. The next section discusses the results of land suitability evaluation for production of selected crops under rainfed conditions.

5.2. Land Suitability Evaluation for Rainfed Production of Major Crops

5.2.1. Agro-climatic analysis

Climate is a very important resource since it influences suitability of a given geographic area for crop and livestock production mainly through its elements like solar radiation, precipitation, temperature, air humidity, and wind speed (Ajadi *et al*., 2011). These climatic factors determine, among others, availability of water and its requirement and heat required for different biochemical processes. In rainfed agriculture, climate determines the length of the growing period for crop production through its influence on availability of water from precipitation. It is, therefore, important to first assess climate of an area before selecting crops for suitability evaluation. On the basis of this, climate of the study area was analyzed in terms of its important attributes for agriculture, particularly selecting crops that best fit the length of the growing period in the study area. The length of the growing period is 239 days, which means a crop with a cycle of up to 239 days can be grown in the study area provided that soil and landscape attributes are equally suitable. Because of the bimodal nature of the rainfall distribution, there are two humid periods. The first one occurs between April and May during the small rainy season locally called *Belg*, while the second humid period occurs between July and August in the main rainy season locally known as *Kiremt*. The humid period is the period during which the soil moisture storage is filled. In the study area, farmers are using the small rainy season to grow crops that have short cycle. The major crops, however, are grown during the main rainy season although planting may be done towards the end of the small rainy season.

5.2.2. Overall land suitability evaluation

Sorghum

Sorghum is one of the major cereal crops grown in the study area. However, the yield of the crop has been far below what climate of the study area and genetic potential of the crop could support.

The mean sorghum yield at national level for the period 2015-2018 was 2.6 t ha^{-1}, while the average yield in the study area for the same period was 1.29 t ha^{-1}. Because of this low productivity, the study area has been food insecure for the last many years. Unraveling the underlying causes for this low productivity was felt necessary. Land suitability evaluation provides answers to such challenges (Gong *et al*., 2012; Elsheikh *et al*., 2013; Ahmed *et al*., 2016; Singha and Swain, 2016; Mousavi *et al*., 2017; Hamere and Teshome, 2018; Mazahreh *et al*., 2018; Mwendwa *et al*., 2019). Accordingly, the current suitability evaluation identified important climate, soil and landscape attributes that are not at optimum level for optimum sorghum productivity under the current management by subsistence farmers. The maximum overall current land suitability class for production of late-maturing sorghum is 'marginally suitable (S3c for SMUs 1-3 and S3wfc for SMU4)'. The potential suitability also remains 'marginally suitable (S3c)' due to the low mean growing period temperature in the study area. Gizachew (2015) reported slope, temperature, available phosphorus, and soil depth as limiting factors for rainfed production of sorghum in Guang Watershed. Teshome *et al*. (2013) also found fertility as a limiting factor for rainfed sorghum production in Abebo area of western Ethiopia. Similarly, Kahsay *et al*. (2018) conducted a land suitability evaluation using GIS for sorghum production in north semi-arid Ethiopia and identified a number of climate, soil and landscape attributes as limiting factors for sorghum production. Al-Mashreki *et al*. (2011) did land suitability evaluation for sorghum production in Yemen and found out that slope, soil in general, erosion, and climate were the limiting factors with different levels of sensitivity.

The low temperature is expected since significant portion of the study site is a high altitude area (1750-2775 m.a.s.l). In order to enhance productivity of sorghum, the current limitations related to soil fertility and other landscape attributes need to be addressed. Integrated soil fertility management can offer the preferred solutions for improving the low fertility status of the soils and enhance sorghum productivity. Additionally, appropriate soil and water conservation practices ought to be put in place in order to reduce erosion hazard expected to occur from cultivation of steep slopes. Similarly, the drainage problem in the lower parts of the study area needs to be addressed through appropriate surface and subsurface drainage systems. This requires the cooperation of the local community among themselves and support from government to cover the high cost associated with establishment of drainage systems.

The temperature-related limitation may not be fixed easily unless varieties that can perform under low temperature conditions are developed. This has to be taken as a long-term strategy. On the other hand, if future climate change causes rise in temperature, it may create a favorable environment for growing the late-maturing sorghum varieties successfully in the study area. The successful production of this crop can result in more carbon sequestration and reduction of greenhouse gas emission. However, the biomass production potential of this variety under a changing climate needs to be projected or tested using appropriate models under different Representative Concentration Pathways (RCPs) and time slots before hasty generalizations or recommendations are made.

Maize

Maize is another important cereal crop grown in the study area. Similar to sorghum, its productivity has been unsatisfactory for the last many years. The four-year (2015-2018) average yield of maize at national level was 3.61 t ha^{-1}, whereas the average maize yield of the study area during the same time period was 1.61 t ha^{-1}. This might be related to environmental and management problems. Unless those problems are identified, solutions are sought for and implemented, the productivity of the crop cannot be raised. Evaluating the suitability of the climate, soil and landscape attributes could help in identifying the limitations and suggesting feasible remedial measures. Results of the suitability analysis suggested that maize could be grown in the study area. However, some of the environmental attributes at their current status are not optimum for maize production. The limitations are almost similar with that of sorghum. Similar to sorghum, rise in temperature in the area due to climate change might favor the production of the late-maturing maize in the study area. In the long-term, it may also be important to develop maize varieties that can tolerate or perform better under low temperature conditions if the climate remains the same. To come to comprehensive recommendation on alternative land uses that enhance carbon sequestration and reduce greenhouse gas emission, the biomass production potential of the late-maturing maize varieties under business-as-usual and alternative adaptation measures needs to be evaluated under projected future climate.

The results of a land suitability evaluation done to assess the suitability of Chawaka Settlement area in Ilu Aba Bora zone of Western Ethiopia for rainfed production of sorghum (*Sorghum bicolor* L.) and maize (*Zea mays* L.) indicated that soil fertility and landscape, and climatic factors affect the optimum production of late-maturing varieties of the two crops (Dawit, 2010). Teshome *et al*. (2013) evaluated suitability of Abobo area in western Ethiopia for rainfed production of three major crops (maize, upland rice, and sorghum). Their results indicate that both climate and soil and landscape attributes limit the production of these crops in which soil depth, wetness, and soil fertility were found to be among the most limiting factors. Because of these limitations, the actual suitability classes ranged from marginally suitable to moderately suitable. Other studies (e.g., Abagyeh *et al*., 2016; Jimoh *et al*., 2016; Adzemi *et al*., 2017) did land suitability evaluation for maize production in different parts of the world and reported different levels of suitability due to the presence of climate and soil and landscape attributes that are below the optimum level for successful producton of the crop. The results of the current study and other similar studies clearly demonstrate that climate, soil, and landscape attributes such as slope are limiting optimum crop production in the country. That could be one reason why the country has been struggling to ensure food security for the last many years. In order for the agriculture sector to be more productive and supportive in fighting climate change through sequestration of greenhouse gases, land must be used according to its suitability and managed based on deficiencies identified for ensuring sustainability. Because maize and sorghum have more or less similar requirements, management recommendation suggested for sorghum can also work for maize.

Coffee arabica

Coffee arabica is one of the cash crops grown in eastern part of the country. This eastern part of the country produces the best quality coffee in the country. The major limiting attributes for successful production of coffee in the study area under the current low-level of management include poor drainage (SMU 1, 2 & 4), low precipitation (SMU 1,2,3 &4), soil reaction (pH-H_2O) (SMU 2 & 3), and effective depth (SMU 2). As indicated in Sys *et al*. (1993), coffee requires deep, slightly acidic, friable, permeable, well drained, and fertile clay to clay loam soil for optimum growth. The roots have high oxygen requirement. In order to improve the productivity of coffee in the study area, the limitations related to the above-mentioned attributes ought to be addressed through appropriate management interventions. Coffee is a shade loving plant. Coffee agroforestry could provide multiple benefits in the study area for coffee production. The results of the current suitability evaluation revealed that the area is marginally suitable

(S3wc) for optimum production of coffee. It is well documented that coffee plants are sensitive to climate and soil pH (Descroix and Snoeck, 2004; Silva *et al*., 2013; Wang *et al*., 2015). Studies have shown that Arabica coffee (*Coffea arabica*) production is affected by climate change within current regions of production. However, coffee regions in Ethiopia are expected to become more suitable for Arabica coffee (Ovalle-Rivera *et al*., 2015). The same study confirmed that in the East African sub-region annual rainfall is predicted to increase somewhat, from 1400 mm to 1440 mm, and the dry season to decrease from 5 to 4 months. Hence, the study area will be more suitable for production of coffee in the decades to come. It is also important to look into availability of better adapted genetic material that can permit farmers to extend coffee production to marginally suitable sites (Haggar *et al*., 2011; Lopez-Rodriguez *et al*., 2015).

Upland rice (Oryza sativa)

Rice is not a commonly grown crop in Ethiopia. The same is true in the study area as well. This is so not because Ethiopia is not suitable for rice production, but it is because the people are not used to growing it. It may be an alternative if tried. The major limiting attributes for successful production of upland rice in the study area under rainfed and low-level of management include precipitation (SMU 1, 2, 3 & 4) and temperature (SMU 1, 2, 3 & 4). All the limitations are permanent and uncorrectable by nature, which makes the maximum current land suitability class 'permanently not suitable (N2c for all the soil mapping units)' for production of upland rice. Similarly, the sub-watershed will remain potentially 'not suitable (N2c)' for production of upland rice. In agreement with the current finding, Shahram *et al*. (2013) identified climate, specifically mean temperature, as a limiting factor (N1) for production of rice in Iran. Teshome *et al* (2013) identified wetness (N), depth (S3), fertility (S3), and moisture (S3) as limitations for rainfed production of upland rice in Abobo Area of western Ethiopia. Similarly, a study in Indonesia reported rainfall, slope, drainage, and fertility as major limitations for low management rainfed upland rice production (Suheri *et al*., 2018).

Finger millet

Finger millet is not a commonly grown cereal crop in the study area. However, very few farmers often grow it as a border crop. Precipitation, low temperature, and steep slope were the major limiting attributes for optimum finger millet productivity. Because of these limitations, the current suitability class is ‘marginally suitable (S3c) for all SMUs except SMU3’. Limitation related to inadequate moisture supply from rainfall can be improved by irrigation if there exists good quality and dependable quantity of irrigation water and other required infrastructure for irrigation. Irrigation requires good investment, which most subsistent farmers do not afford to pay. The low temperature and steep slope limitations are almost impossible to correct with the capacity of the subsistent farmers. Huge investment is required. Due to the permanent nature of the mentioned limitations, therefore, the sub-watershed remains potentially ‘marginally suitable (S3c) for all SMUs except SMU3-S3tc’ for production of finger millet. In line with this, Tesfaye *et al*. (2017) reported that climatic factors affect optimum production of finger millet in northern Ethiopia. On the other hand, Mustafa *et al*. (2011) confirmed that finger millet can be grown in nutrient poor soils, but may not perform very well in high pH soils.

In General, the results of most recent studies clearly indicate that low soil fertility and landscape attributes are limiting the optimum production of most crops in the subsistent agricultural systems of Ethiopia. Climate, particularly temperature and rainfall, are also limiting the successful production of most crops. In order to enhance agricultural production and productivity and amplify the contribution of agriculture in fighting against climate change through carbon sequestration and reduced greenhouse gas emissions, the crops should be matched with their natural agro-ecology and soil fertility limitations should be addressed for each location using locally affordable and environmentally friendly management interventions. As it is clear from results of this suitability study, the different mapping units under agriculture at Hades Sub-watershed are not highly or even moderately suitable for production of the selected crops. The crops have been grown in the area for the last many years without giving the expected benefits. Because of this and other related reasons, the area has been food insecure. Furthermore, because of the expected low productivity, the current land uses are not good enough in sequestering carbon and mitigating climate change. An alternative land use that has higher productivity and carbon sequestration potential has to be sought for under the future looming climate change. It is only then that a resilient ecosystem and society will be created. The next section discusses projected climate, biomass yield, and biomass carbon of long-maturing sorghum and maize varieties under two RCPs during two time slots.

5.3. Projection of Carbon Sequestration Potential of Selected Land Utilization Types under Projected Climate

5.3.1. Projected climate

Rainfall

The current study revealed that the percent deviation of rainfall from the baseline varied with the type of model used. Some of the models predicted high percentage variability from the baseline, while the others projected low percentage deviation from the baseline. In consent with this result, Abdu *et al*. (2009) reported high variability of rainfall, projected using HadCM3 model, during the rainy season in Blue Nile region of Ethiopia. Furthermore, the results of rainfall variability are influenced by the RCPs considered for this study. It was also noted that JJAS rainfall will decrease during the Near-Century under RCP4.5. The result was in agreement with the findings of Huntingford *et al*. (2005), Vizy and Cook (2012), and Laprise *et al*. (2013), who reported a decreasing rainfall and a drying condition over east Africa. The variability in rainfall will be for both main rainy season and small rainy season, with variability of the latter expected to be small. According to rating of rainfall variability suggested by Hare (1983), the percentage variability of rainfall for the small rainy season under RCP4.5 and Near-Century ranges from low (< 20%) to moderate (20-30%). Nevertheless, contrasting results in percentage rainfall variability were projected by the different models under RCP4.5 during the Mid-Century (NMSA, 1996).

It is well understood that climate models projected a large variability of rainfall at global scale and such variation in projection of rainfall by different models is obvious (Schär *et al*., 2004; Fischer and Schär, 2010). Similarly, annual rainfall projection in Ethiopia is dependent on the type of models used (Conway and Schipper, 2011). Future projections of rainfall change are subject to substantial uncertainties and model simulations disagree on the likely direction and magnitude of change. According to Daron (2014), on average, some climate models projected a shift to slightly wetter condition over East Africa, especially for RCP8.5 emission scenario, while some other models projected drier average conditions (Laprise *et al*., 2013; Vizy and Cook, 2012). The current result is in agreement with the findings of Ayalew *et al*. (2012) who reported a decreasing trend in annual rainfall by 2050s (Mid-Century) in Northern Ethiopia. This decrease in rainfall might exacerbate food crisis in the country. Woldeamlak (2006) emphasized that rainfall variability has been one of the major causes of food insecurity and famine in

Ethiopia. Though the coefficient of variation of rainfall was found to be low (≤ 20%), inter annual variability in the length of the growing season was commonly challenging to rainfed agriculture (Conway and Schipper, 2011; Kassie *et al*., 2013).

Temperature total

Temperature is another important element of climate expected to change in the future. Results of the current study revealed that both the minimum and maximum temperature will increase during the Near- and Mid-Centuries under both emission scenarios. In agreement with this, earlier studies made using model projections by Schär *et al*. (2004) and Fischer and Schär (2010) demonstrated that there will be an increase in mean temperature. Additionally, IPCC (2007) reported a likely 2 -3 °C changes in temperature over the next 30 -50 years. Furthermore, simulation studies that involved three climate models by Daron (2014) revealed a general rise in temperature across East Africa during the 2040's. This rise in temperature will affect suitability of a given area for different life forms on this planet. From crop production point of view, increase in temperature may expose crops to heat stress. As pointed out by Gornall *et al*. (2010) higher temperatures will curtail crop performance by increasing the heat stress and water loss by evaporation. Moreover, Liu (2010) demonstrated that rise in temperature reduces crop yield by shortening the length of the growing season. In the study area, however, the rise in temperature could favor the growth of crops like sorghum and maize, which require relatively higher temperature.

5.3.2. Model calibration and validation results

In the era of climate change, it is important to assess the likely impacts of climate change on crop performance and management requirements. Simulation models may help in quantifying the influence, for instance, of water on yield at farm level and, hence, aid as supportive tools in water and irrigation management (Heng *et al*., 2009). However, models need to be calibrated and validated for local context before they are used. The values of the selected model performance evaluation indices revealed the presence of good agreement between the observed and simulated grain yield of maize (Mibulo and Kiggundu, 2018; Ran *et al*, 2018). Zeleke (2019) used AquaCrop to evaluate the effect of agronomic management practices that include sowing date and rate, and scheduling irrigation on faba bean and found that the model works well in simulating yield. For instance, the root mean square error normalized (RMSEN) value indicates that maize and sorghum yields were estimated with high accuracy since it was less than 10% (Hsiao *et al*, 2009). The RMSE represents a measure of the overall or mean deviation between observed and simulated values, and is a synthetic indicator of the absolute model uncertainty (Heng *et al*., 2009). Therefore, the results of the model calibration and validation indicated that AquaCrop model can simulate biomass yield of the two crops with high accuracy (Van Gaelen *et al*., 2015). Other studies also reported that AquaCrop performed satisfactorily in predicting grain yield of maize (Heng *et al*., 2009) and winter wheat (Jin *et al*., 2014).

5.3.3. Projected biomass production

Sorghum

Many studies have clearly indicated the trend of greenhouse gas emission from the agriculture sector (e.g., Tbiello *et al*., 2015; IPCC, 2018). The future agriculture must contribute to fighting climate change through sequestration of greenhouse gases and increasing productivity per unit area. One way of achieving this is through evaluation of biomass production of crops under future climate. The current study evaluated the biomass production potential of late-maturing sorghum variety as one of the relatively better suited crops in the study area. Planting earlier than the normal planting time is expected to decrease sorghum biomass production. This could be due to water stress that could affect germination and growth of sorghum seedlings (Ju *et al*, 2013). On the other hand, late planting with and without supplementary irrigation produced about the same amount of biomass, suggesting that sorghum may not need supplementary irrigation if planted late. Even though delayed planting is naturally expected to shorten the length of available growing period (FAO, 2012), it inexplicably increased biomass yield as compared to the baseline. This might suggest that sorghum is less sensitive to terminal moisture stress. The models performed differently with regard to projection of biomass yield under the two RCPs and time slots. Some predicted increase in biomass yield, while the others projected otherwise.

In general, the results of the current study confirmed the possibilities of enhancing sorghum biomass yield by adjusting planting time (PD_o+15D) (Assenge *et al*., 2011; Alshikh *et al*., 2017). It was also noted that sorghum will not respond well to supplementary irrigation, which could be due to better water productivity of the crop under the given scenarios and climate projections.

Sorghum exhibits physiological responses that allow continued growth under water stress (Dugas *et al*., 2011). Delayed leaf senescence, high chlorophyll content and chlorophyll fluorescence ratio as well as low canopy temperature and high transpiration efficiency are physiological traits that confer drought tolerance to sorghum (Kapanigowda *et al*., 2013). In connection with this, results of the current study highlighted that applying supplementary irrigation for sorghum production may not be that much profitable for the study area. Instead, delaying sorghum planting by 15 days (PD_o+15D) was found to be the best adaptation option for maximizing sorghum biomass yield. This may indicate that good germination and the consequent good stand are highly important for sorghum biomass yield.

Contrary to the findings of the current study, Alshikh *et al*. (2017) reported increase in sorghum yield in Sudan when early sowing is used for most of the their study areas, while a yield reduction of up to 43% was projected when sowing is delayed by about 15 days from the recommended date (July 15 to August 1). Nevertheless, the same authors pointed out that, stations with high rainfall showed little variations in inter-annual yields but with a tendency towards high yields. Similarly, Fischer (2009) projected slight increment (4%) in sorghum yield by 2020s (Near-century) and 2050s (Mid-century) in East Africa. However, different authors (Tingem *et al*., 2009; Srivastava *et al*., 2010) reported the presence of variation of biomass outputs among different models.

Maize

Similar to sorghum, the tested models projected different trends of maize biomass yield. However, the models indicated that adjusting planting dates and use of supplementary irrigation would affect maize biomass yield. For a given planting date under a given RCP and time slot, some models projected increase in biomass yield, while the others projected lower biomass yield than the baseline. With regard to time slot, the models responded differently. Even within the same model, projected biomass followed different trends under Near- and Mid-Centuries. Some models predicted increase in biomass yield in the MC as compared to NC. This could be related to the slightly high minimum and maximum temperature in the Mid-Century compared with the Near-Century that favor biomass production of maize (Thornton *et al*., 2009). Previous studies also projected different trends of maize biomass yield. Lobell *et al*. (2008a, b) projected significant decline in maize yield due to climate change for as early as 2030. Similarly, Kassie *et* *al*. (2015) projected reduction of maize yield by about 20% for central rift valley of Ethiopia. In China, Lv *et al*. (2019) projected 0- 24% yield reduction of maize during 2010–2099 relative to 1976–2005. Araya *et al*. (2015), however, indicated a slight increment of maize biomass yield under future climate in southwestern Ethiopia.

5.3.4. Projected biomass carbon and its CO_2 equivalent for sorghum and maize

Sorghum (Muyira-1)

The future agriculture should reduce emission and increase sequestration of greenhouse gases. Future land uses should consider improving both productivity and sequestration of greenhouse gases. In this study, organic carbon production was calculated from the biomass yield simulated by the AquaCrop model. As a result, the trends of biomass carbon and its carbon dioxide equivalent followed the trend of the biomass yield. Under a given RCP and for a given adaptation measure, all the models projected equal biomass carbon in majority of the cases. For a given adaptation measure, all the models projected a higher biomass carbon under RCP8.5 than RCP4.5, suggesting that rise in temperature and CO_2 level would benefit sorghum production in the coming 50 years in the study area. The results indicate that implementing late planting alone or in combination with supplementary irrigation can increase biomass carbon by 7.84% over the baseline under RCP4.5. On the other hand, the same adaptation measure would increase the biomass carbon by 3.62% over the baseline under RCP8.5. Under RCP8.5, projections by all models reveal that late planting would reduce biomass carbon than the baseline planting. This result indicates that early planting could result in low biomass carbon production due probably to the effect of early moisture deficit stress on germination and eventually biomass yield. Moreover, the results indicate that introducing supplementary irrigation will not result in more biomass carbon than just late planting. Hence, delaying sowing date by 15 days for sorghum could be one of the adaptation options to enhance biomass carbon under future climate change (Alshikh *et al*., 2017). In general, the results obtained in this study testify that it is possible to project carbon sequestration from a given land use using the AquaCrop model.

Maize (BH661)

The result indicated presence of reduction in maize biomass carbon and CO_2 equivalent for early planting compared to the other adaptation measures. Under both RCPs, maize will perform better in terms of biomass carbon when late planting is combined with supplementary irrigation. With very few exceptions, the projected results indicate that, for a given adaptation measure and RCP, the biomass carbon will not vary during the time slots. With the exception of the reference planting date and late planting, the biomass carbon under RCP8.5 will be slightly higher than that under RCP4.5, implying that maize will respond positively to the increased temperature and CO_2 level. Lv *et al*. (2019) found that introduction of new adaptable cultivars and adjustment of sowing dates can improve maize biomass yield and biomass carbon. The current findings revealed that as high as 2.33 t C ha^{-1} can be obtained from late-maturing maize by modifying the planting dates and introducing supplementary irrigation in the coming 50 years.

In general, the results of the current study indicated that AquaCrop model can be used to simulate biomass yield of sorghum and maize in the Near- and Mid-century under RCP 4.5 and RCP 8.5 with reasonable accuracy. Because of inherent differences among the climate models, some variations in projected biomass yield and biomass carbon of the two crops were observed under the time slices and RCPs considered in this study. The results also clearly indicate that AquaCrop can be used to evaluate the effects of adaptation options on biomass yield and carbon sequestration. In general terms, it can be concluded that sorghum could produce better biomass and, hence, sequester higher biomass carbon in the Near- and Mid-centuries under RCP4.5 and 8.5 as compared to maize. Late planting for sorghum and late planting plus supplementary irrigation for late-maturing maize could give better biomass yield and carbon sequestration under future climate.

In addition to the benefit likely to be obtained from improved biomass and grain yield, the local farmers can also generate additional income from selling the carbon sequestered in the soil. This means that improving the soil carbon sequestration could enhance soil productivity by improving soil fertility and generate additional income from trading carbon. However, this requires a strong commitment towards implementing the carbon trading protocols as well as improving the carbon pricing per unit quantity of carbon sequestered.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusions

Realizing the importance of the agriculture sector in adaptation to and mitigation of climate change, the study assessed carbon stock under major land use/cover types, undertook physical land suitability evaluation for rainfed production of major crops, and projected biomass yield and biomass carbon of late-maturing sorghum and maize for the coming 50 years under two RCPs (RCP4.5 and RCP8.5). The research came-up with informative empirical information on the respective topics. From the results obtained, the following core conclusions can be drawn:

1. Carbon stock in the study area varies with land use/cover type. Regardless of these differences, the carbon stock under the respective land use types is generally low in the study area, which implies depletion of carbon from the different pools. From among the land uses, the cropland is the most depleted land use type. This depletion is the result of inappropriate utilization and management of the carbon sources such as crop residues, litter, and debris. On the other hand, the low carbon stock, particularly in the soils, implies that there is high potential for sequestering and storing more carbon in those systems. The study has demonstrated the importance of soil in storing carbon that exceeds the amount in vegetation biomass by many folds.
2. Under the current low level of management, the climate, soil and landscape features of the study area are not at the optimum state for rainfed production of sorghum, maize, coffee, finger millet, and upland rice. Some of the limitations (e.g., soil fertility) are correctable, while the others (e.g., topography and climate) are permanent in nature. The limitations are believed to reduce biomass and grain/seed yield, which in turn results in low carbon sequestration and storage. Continuing with the current land use types as they are will exacerbate organic carbon depletion and greenhouse gas emission. The limitations need to be addressed or land units should be used according to their suitability to enhance productivity and carbon sequestration on a sustainable basis.
3. Over the coming 50 years, the study area will experience change in precipitation amount and temperature. General reduction in main rainy season's precipitation and modest rise in minimum and maximum temperature are projected. The rise in temperature will favor

growth of late-maturing sorghum and maize varieties, while the reduction in main season precipitation requires intervention to avoid crop failure due to moisture deficit stress.

4. With the implementation of appropriate adaptation measures, late-maturing sorghum and maize varieties can produce good biomass and biomass carbon under climate change over the coming 50 years. Late planting for sorghum and late planting plus supplementary irrigation for maize resulted in better model-predicted biomass yield and carbon sequestration under RCP4.5 and RCP8.5. Practicing these types of land utilization types in the study area is expected to increase carbon sequestration and reduce greenhouse gas emission from the agriculture sector, particularly smallholder subsistent farming systems.
5. The results obtained revealed that AquaCrop can be used to evaluate management scenarios in terms of their potential for adaptation to or mitigation of climate change by simulating biomass yield, from which biomass carbon can be calculated.

6.2. Recommendations

The study has identified key areas that require intervention in order to curb the current challenges and enhance the contribution of the smallholder farming systems towards climate change mitigation and adaptation through carbon sequestration. Based on the core challenges identified, the following recommendations are put forward:

- Interventions that improve and maintain the carbon stock under the different land use/cover types should be identified, tested, and implemented in economically feasible and environmentally sound ways.
- The different mapping units should be used according to their best suitability in order to abate further organic carbon depletion and foster carbon sequestration.
- The correctable limitations to crop production identified by the study should be addressed following scientific approaches in the best possible way in assessing and implementing feasible appropriate management interventions.
- Future research should focus on developing species-specific allometric equations for dominant tree species in the study area for predicting the vegetation carbon stock with better accuracy.

- The suitability evaluation should be expanded to other alternative land uses that have the potential to reduce greenhouse gas emission through enhancing productivity as well as carbon sequestration.
- The AquaCrop model should be tested, using experimentally generated data, on more crops and their varieties, management and climate scenarios in order to guide future decisions in a better way.
- Development of new varieties of crops that are adaptable to the current and future climate should be undertaken at least as a long-term strategy.
- Since the change in climate, particularly rise in temperature, will favor the growth of late-maturing sorghum (Muyira-1) and maize (BH661) varieties, these crops should be recommended to local farmers in the study area after their performance is evaluated experimentally.

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APPENDIX TABLES

Appendix Table 4.1: Above and belowground biomass t ha^{-1}) of natural forest and coffee agroforestry at Hades sub-watershed

Plot No	Natural Forest				Coffee Agroforestry			
	Trees > 30cm dbh		Trees 5-30 cm dbh					
	AG	BG	AG	BG	Coffee shrub		Shade Tree	
	≥ 30 cm		≤30 cm and ≥5cm		AG	BG	AG	BG
1	116.7	23.3	0	0	11.43	2.29	16.70	3.34
2	96.3	19.3	3.8	0.8	10.02	2.00	23.04	4.61
3	110.1	22.0	20.0	4.0	11.18	2.24	13.78	2.76
4	76.8	15.4	12.3	2.5				
5	65.3	13.1	14.0	2.8				
6	60.2	12.0	11.4	2.3				

AG= Above Ground Biomass, BG = Below Ground Biomass, dbh = diameter at breast height

Appendix Table 4.2: Mean monthly value of temperature (Min & Max), humidity, wind speed, radiation and potential evapotranspiration of Hades sub-watershed

Month	Min Temp (°C)	Max Temp (°C)	Humidity (%)	Wind (km/day)	Sun (hours)	Rad (MJ/m²/day)	ETo (mm/month)
January	9.2	18.3	72	156	7.3	18.4	95.98
February	10.0	20.1	70	156	7.4	19.7	98.26
March	10.6	20.6	71	164	7.1	20.2	115.38
April	11.0	19.7	78	156	6.1	18.9	102.08
May	11.0	19.5	81	173	5.9	18.2	99.96
June	10.5	18.7	85	233	4.9	16.3	85.29
July	9.6	18.1	87	216	4.1	15.3	81.42
August	9.3	17.1	90	233	4.0	15.4	75.56
September	10.5	18.4	83	156	5.8	18.1	91.04
October	10.8	18.8	74	138	7.6	20.2	106.30
November	10.1	18.9	68	147	8.0	19.6	101.41
December	10.4	18.6	65	138	8.2	19.2	102.35
Average	10.3	18.9	77	172	6.4	18.3	1155.03

Appendix Table 4.3: Mean monthly rainfall of Hades Sub-watershed

	Months											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainfall (mm)	16	26	52	111	158	85	115	189	85	46	39	9
Eff.rain (mm)	15.6	24.9	47.7	91.3	118.1	73.0	93.8	131.8	73.4	42.6	36.6	8.9

Appendix Table 4.4: Climate suitability for production of late-maturing sorghum and maize varieties, finger millet, coffee and upland rice at Hades sub-watershed, eastern Ethiopia

Climate characteristics	Sorghum (180-240 days)	Maize (180-210 days)	Finger Millet (120 – 150 days)	Coffee	Upland rice (120)
Mean growing period temperature (°C)	S3	S3	S3	S3	N2
Length of growing period (days)	S2	S2	S2	S1	S1
Total growing period rainfall (mm)	S1	S1	S3	S3	N2
Overall climate suitability	S3	S3	S3	S3	N2

Appendix Table 4.5: Overall soil and landscape suitability classes for production of late-maturing sorghum and maize varieties, finger millet, coffee and upland rice at Hades sub-watershed, eastern Ethiopia

Soil mapping unit	Sorghum (180-240 days)		Maize (180-210 days)		Coffee		Finger millet (120 – 150 days)		Upland rice (120 days)	
	Actual	Potential	Actual	Potential	Actual	Potential	Actual	Potential	Actual	Potential
SMU1	S2wf	S1	S3w	S2s	S3wc	S3c	S3c	S3c	N2c	N2c
SMU2	S2wsf	S2s	S3wf	S2s	S3wsfc	S3sc	S3c	S3c	N2c	N2c
SMU3	S2tf	S2t	S2tf	S2t	S3fc	S3c	S3tc	S3tc	N2c	N2c
SMU4	S2wf	S1	S3w	S2s	S3wc	S3c	S3c	S3c	N2c	N2c

Appendix Table 4.6: Soil and landscape suitability of individual soil mapping unities (SMUs) for production of late-maturing sorghum and maize varieties, finger millet, coffee and upland rice at Hades sub-watershed, eastern Ethiopia

SMU1

Soil/landscape characteristics	Value	Sorghum	Maize	Coffee	Finger millet	Upland Rice
Slope (%)	7	S1	S1	S1	S1	S1
Drainage	Imperfectly drained	S2	S3	S3	S2	S1
Flooding	No flooding	S1	S1	S1	S1	S1
Texture	Sandy clay	S1	S2	S1	S1	S1
Coarse fragment (%)	1.0	S1	S1	S1	S1	S1
Effective depth (cm)	144	S1	S1	S2	S1	S1
Soil reaction (pH-H_2O)	6.99	S1	S1	S2	S1	S1
Apparent CEC (cmol(+) kg^{-1} clay)	95.3	S1	S1	S1	S1	S1
Sum of basic cations (cmol (+) kg^{-1} soil	38.44	S1	S1	S1	S1	S1
Organic matter (%)	2.64	S2	S2	S1	S1	S1
Available Phosphorous (mg kg^{-1})	6.55	S2	S2			
Overall SL class (Actual)		**S2wf**	**S3w**	**S3w**	**S2w**	**S1**
Potential suitability soil/landscape		**S1**	**S2s**	**S2s**	**S1**	**S1**

SMU2

Soil/landscape characteristics	Value	Sorghum	Maize	Coffee	Finger millet	Upland Rice
Slope (%)	5.5	S1	S1	S1	S1	S1
Drainage	Imperfectly drained	S2	S3	S3	S2	S1
Flooding	No flooding	S1	S1	S1	S1	S1
Texture	Sandy clay	S1	S2	S1	S1	S1
Coarse fragment (%)	0.58	S1	S1	S1	S1	S1
Effective depth (cm)	94	S2	S2	S3	S1	S1
Soil reaction (pH-H_2O)	7.70	S1	S3	S3	S2	S2
Apparent CEC (cmol(+) kg^{-1} clay)	124.2	S1	S1	S1	S1	S1
Sum of basic cations (cmol (+) kg^{-1} soil	48.12	S1	S1	S1	S1	S1
Organic matter (%)	2.50	S2	S2	S1	S1	S1
Available Phosphorous (mg kg^{-1})	9.02	S2	S2			
Overall LS SC (Actual)		**S2wsf**	**S3wf**	**S3wsf**	**S2wf**	**S2f**
Potential suitability soil/landscape		**S2s**	**S2s**	**S3s**	**S1**	**S1**

SMU3

Soil/landscape characteristics	Value	Sorghum	Maize	Coffee	Finger millet	Upland Rice
Slope (%)	16	S2	S2	S2	S3	N1
Drainage	Excessively well drained	S1	S1	S1	S2	S2
Flooding	No flooding	S1	S1	S1	S1	S1
Texture	Sandy clay loam	S1	S1	S2	S1	S2
Coarse fragment (%)	10.0	S1	S1	S1	S1	S1
Effective depth (cm)	101	S1	S1	S2	S1	S1
Soil reaction (pH-H_2O)	7.47	S1	S2	S3	S1	S1
Apparent CEC (cmol(+) kg^{-1} clay)	113.0	S1	S1	S1	S1	S1
Sum of basic cations (cmol (+) kg^{-1} soil	29.17	S1	S1	S1	S1	S1
Organic matter (%)	2.48	S2	S2	S1	S1	S1
Available Phosphorous (mg kg^{-1})	9.08	S2	S2			
Overall SL class (Actual)		**S2tf**	**S2tf**	**S3tf**	**S3t**	**N1t**
Potential suitability soil/landscape		**S2t**	**S2t**	**S3t**	**S3t**	**N1t**

SMU 4

Soil/landscape characteristics	SMU 4	Sorghum	Maiz e	Coffee	Finger millet	Upland rice
Slope (%)	3.5	S1	S1	S1	S1	S1
Drainage	Imperfectly drained	S2	S3	S3	S2	S1
Flooding	No flooding	S1	S1	S1	S1	S1
Texture	Sandy clay	S1	S2	S1	S1	S1
Coarse fragment (%)	9.3	S1	S1	S1	S1	S1
Effective depth (cm)	139	S1	S1	S2	S1	S1
Soil reaction (pH-H_2O)	7.02	S1	S2	S2	S1	S1
Apparent CEC (cmol(+) kg^{-1} clay)	124.7	S1	S1	S1	S1	S1
Sum of basic cations (cmol (+) kg^{-1} soil	43.00	S1	S1	S1	S1	S1
Organic matter (%)	2.52	S2	S2	S1	S1	S1
Available Phosphorous (mg kg^{-1})	16.99	S1	S1			
Overall SL suitability class (Actual)		**S2wf**	**S3w**	**S3w**	**S2w**	**S1**
Potential suitability soil/landscape		**S1**	**S2s**	**S3c**	**S1**	**S1**

Appendix Table 4.7: Climate parameters of the four climate models and multi model ensemble under two emission scenarios

Models	Climate Scenarios																	
	RCP4.5			RCP8.5			RCP4.5			RCP8.5			RCP4.5			RCP8.5		
	RF (mm)			RF (mm)			Tmax (°C)			Tmax (°C)			Tmin (°C)			Tmin		
	FMAM	JJAS	ONDJ	FMAM	JJAS	ONDJ	FMAM	JJAS	ONDJ	FMAM	JJAS	ONDJ	FMAM	JJAS	ONDJ	FMAM	JJAS	ONDJ
CNRM_CMS																		
Baseline	224.5	565.0	104.9	512.9	988.9	181.8	14.7	25.5	14.8	14.6	25.3	14.8	11.1	20.8	12.1	11.1	20.7	12.1
Near century	272.0	550.0	123.0	487.4	1108.0	231.8	15.8	26.9	15.9	15.7	27.2	15.8	12.2	22.1	13.1	12.1	22.4	13.0
Mid century	265.4	615.8	125.5	512.0	1059.0	195.8	10.0	28.1	16.5	16.9	28.0	17.2	12.5	23.2	13.7	13.2	23.3	14.4
GadGem_ES																		
Baseline	195.0	188.2	467.0	359.0	146	96.3	13.8	22.9	15.8	13.9	23.0	15.9	12.6	21.7	14.5	12.7	21.8	14.6
Near century	239.9	387.3	93.5	284.2	399.2	104.2	15.1	24.9	17.5	15.1	25.1	17.3	13.9	23.7	16.1	13.9	23.8	16.0
Mid century	301.9	97.0	323.0	309.2	270.9	131.0	15.9	26.1	18.5	16.4	27.0	19.2	14.7	24.8	17.2	15.2	25.7	17.9
MPI_MSR_LR																		
Baseline	287.8	564.5	93.8	289.0	544.2	93.7	14.4	22.6	15.4	14.4	22.6	15.4	12.7	20.9	13.5	12.7	20.8	13.6
Near century	300.0	543.0	113.0	231.4	527.3	99.6	15.2	24.2	16.7	15.2	24.2	16.7	13.4	22.5	14.7	13.7	22.6	14.7
Mid century	246.8	507.8	117.5	238.5	440	130.0	15.8	24.8	17.1	15.8	24.8	17.1	14.0	23.1	15.1	14.7	24.0	15.8
EC_Earth																		
Baseline	293.5	550.8	94.2	289.9	549	92.3	14.1	22.5	15.0	14.3	22.6	15.0	11.4	19.3	12.7	11.4	19.3	12.8
Near century	291.3	530.8	104.6	416.0	517.3	110.8	15.0	24.7	16.0	15.1	24.5	16.3	12.6	20.7	14.0	12.7	20.7	14.0
Mid century	275.3	530.9	156.7	294.7	495	118.5	15.4	24.6	16.6	15.8	25.3	16.8	13.0	21.3	14.6	13.6	22.0	15.4
MME																		
Baseline	129.9	224.6	92.2	289.9	549	92.3	15.3	25.1	16.6	14.4	23.6	15.6	12.1	20.9	13.3	12.1	20.9	13.3
Near century	275.9	519.2	108.6	209.8	359	77.3	14.4	25.6	15.5	10.7	17.7	11.5	13.2	22.9	14.9	13.1	22.4	14.4
Mid century	272.3	422.9	173.1	189.8	288.3	116.5	15.8	25.9	17.2	16.2	26.3	17.6	14.5	24.3	15.9	9.9	16.6	11.1

Appendix Table 4.8: Sorghum biomass yield (t ha^{-1}) projected using CNRM-CERFACS-CNRM-CM5 climate model for different adaptation measures and time slices under RCP4.5

Year	PDo	PDo-15D	PDo+15D	PDo+15D+Irr	Year	PDo	PDo-15D	PDo+15D	PDo+15D+Irr
2017	34.7	30.8	37.4	37.4	2044	35.0	31.4	37.0	37.0
2018	33.6	29.7	36.7	36.7	2045	34.8	31.2	37.6	37.6
2019	32.0	28.5	35.1	35.1	2046	33.9	29.4	37.3	37.3
2020	34.5	31.9	36.2	36.2	2047	35.1	31.7	37.1	37.1
2021	34.0	31.8	35.8	35.8	2048	35.2	32.1	37.6	37.6
2022	35.5	33.1	37.4	37.4	2049	35.0	31.9	37.5	37.5
2023	30.7	26.9	34.0	34.0	2050	33.3	29.1	36.9	36.9
2024	31.0	26.4	35.0	35.0	2051	35.4	31.1	38.2	38.2
2025	35.0	31.2	37.8	37.8	2052	34.4	30.6	37.4	37.4
2026	36.9	34.2	38.3	38.3	2053	32.3	28.3	35.7	35.7
2027	33.1	28.5	36.6	36.6	2054	35.5	32.2	38.3	38.3
2028	32.5	28.9	35.5	35.5	2055	36.9	34.7	38.4	38.4
2029	33.9	29.8	37.0	37.0	2056	35.4	31.7	37.9	37.9
2030	34.7	31.0	37.7	37.7	2057	36.0	33.3	38.2	38.2
2031	33.9	29.8	37.2	37.2	2058	35.1	32.6	36.9	36.9
2032	31.2	26.9	35.0	35.0	2059	36.0	33.3	37.9	37.9
2033	35.8	33.7	36.9	36.9	2060	37.0	35.1	38.2	38.2
2034	33.1	30.0	36.1	36.1	2061	37.5	35.5	38.7	38.7
2035	33.6	30.3	36.4	36.4	2062	35.6	32.0	38.0	38.0
2036	33.5	29.4	37.0	37.0	2063	34.8	31.5	37.5	37.5
2037	38.1	36.3	38.9	38.9	2064	38.4	36.2	39.3	39.3
2038	33.8	29.2	37.3	37.3	2065	35.7	33.1	37.6	37.6
2039	36.8	34.5	38.2	38.2	2066	35.2	32.4	38.0	38.0
2040	32.3	29.4	34.9	34.9	2067	35.7	32.9	38.1	38.1
2041	36.8	34.0	38.4	38.4	2068	35.1	32.4	37.1	37.1
2042	34.5	30.2	38.0	38.0	2069	34.0	30.3	36.6	36.6
2043	33.1	28.7	36.9	36.9	2070	35.8	33.0	37.5	37.5

Appendix Table 4.9: Sorghum biomass yield (t ha^{-1}) projected using CNRM-CERFACS-CNRM-CM5 climate model for different adaptation measures and time slices under RCP8.5

Year	PDo	PDo-15D	PDo+15D	PDo+15+IR	Year	PDo	PDo-15D	PDo+15D	PDo+15+IR
2017	36.4	32.8	38.0	38.0	2044	37.2	34.1	38.9	38.9
2018	36.7	35.8	37.7	37.7	2045	37.7	34.7	39.1	39.1
2019	36.7	34.6	38.0	38.0	2046	38.8	36.2	39.6	39.6
2020	36.6	33.8	38.1	38.1	2047	37.3	35.1	38.8	38.8
2021	35.1	31.7	37.2	37.2	2048	38.9	36.8	39.6	39.6
2022	35.5	33.7	37.3	37.3	2049	38.2	36.2	39.3	39.3
2023	37.8	35.2	38.7	38.7	2050	38.7	36.9	39.5	39.5
2024	36.1	32.8	38.1	38.1	2051	37.5	34.2	39.2	39.2
2025	37.0	33.2	38.5	38.5	2052	39.0	37.8	39.6	39.6
2026	37.0	35.1	38.3	38.3	2053	37.7	33.8	39.5	39.5
2027	36.2	32.5	38.2	38.2	2054	37.5	34.9	39.1	39.1
2028	38.4	37.2	38.9	38.9	2055	37.9	36.4	39.1	39.1
2029	37.0	35.2	38.1	38.1	2056	38.0	36.1	39.3	39.3
2030	35.2	32.2	37.5	37.5	2057	37.6	34.7	39.1	39.1
2031	36.5	35.1	37.9	37.9	2058	38.2	36.2	39.3	39.3
2032	35.6	32.3	38.1	38.1	2059	39.6	38.3	40.1	40.1
2033	38.7	37.4	39.2	39.2	2060	38.8	36.5	39.8	39.8
2034	36.0	33.9	37.9	37.9	2061	36.8	33.9	39.0	39.0
2035	38.6	36.1	39.4	39.4	2062	39.1	36.2	40.1	40.1
2036	37.3	35.1	38.7	38.7	2063	38.8	36.1	39.9	39.9
2037	38.2	36.0	39.2	39.2	2064	39.4	38.3	40.1	40.1
2038	34.9	32.0	37.3	37.3	2065	39.1	37.5	40.0	40.0
2039	38.3	36.2	39.1	39.1	2066	38.1	36.0	39.6	39.6
2040	38.6	37.5	39.3	39.3	2067	39.9	38.6	40.3	40.3
2041	37.8	36.0	38.9	38.9	2068	39.8	39.0	40.2	40.2
2042	39.2	37.8	39.6	39.6	2069	40.2	39.1	40.4	40.4
2043	38.6	37.5	39.2	39.2	2070	38.9	37.7	40.0	40.0

Appendix Table 4.10: Sorghum biomass yield (t ha^{-1}) projected using ICHEC-EC-Earth climate model for different adaptation measures and time slices under RCP4.5

Year	Pdo	PDo-15	PDo+15	PDo+15+IR	Year	Pdo	PDo-15	PDo+15	PDo+15+IR
2017	37.6	35.4	38.4	38.4	2044	37.2	35.5	38.5	38.5
2018	37.0	34.3	38.3	38.3	2045	37.8	35.4	39.1	39.1
2019	35.5	32.7	37.7	37.7	2046	37.7	34.7	38.9	38.9
2020	36.4	34.8	37.8	37.8	2047	37.3	35.5	38.8	38.8
2021	36.0	34.3	37.4	37.4	2048	37.9	35.8	39.2	39.2
2022	37.6	35.9	38.4	38.4	2049	37.7	35.6	39.0	39.0
2023	34.4	31.4	37.2	37.2	2050	37.3	34.1	39.0	39.0
2024	35.4	31.9	37.7	37.7	2051	38.4	36.1	39.2	39.2
2025	38.1	35.7	38.8	38.8	2052	37.7	35.1	39.0	39.0
2026	38.4	37.3	38.8	38.8	2053	36.1	33.1	38.6	38.6
2027	37.0	33.9	38.5	38.5	2054	38.5	36.2	39.4	39.4
2028	35.8	33.1	37.8	37.8	2055	38.5	37.3	39.3	39.3
2029	37.3	34.7	38.6	38.6	2056	38.1	36.0	39.3	39.3
2030	37.9	35.4	38.6	38.6	2057	38.4	36.5	39.4	39.4
2031	37.5	34.6	38.6	38.6	2058	37.1	35.5	38.8	38.8
2032	35.4	32.0	37.9	37.9	2059	38.1	36.4	39.3	39.3
2033	37.1	36.0	38.4	38.4	2060	38.4	37.3	39.2	39.2
2034	36.4	33.8	38.4	38.4	2061	38.9	37.8	39.4	39.4
2035	36.6	34.3	38.3	38.3	2062	38.2	36.2	39.2	39.2
2036	37.4	34.3	38.6	38.6	2063	37.8	35.4	39.2	39.2
2037	39.0	38.3	39.2	39.2	2064	39.4	38.7	39.7	39.7
2038	37.6	34.6	38.8	38.8	2065	37.8	36.1	39.1	39.1
2039	38.3	37.2	39.1	39.1	2066	38.2	35.8	39.5	39.5
2040	35.2	32.9	37.5	37.5	2067	38.3	36.2	39.4	39.4
2041	38.5	37.2	39.2	39.2	2068	37.3	35.6	39.0	39.0
2042	38.3	35.3	39.3	39.3	2069	36.9	34.6	39.0	39.0
2043	37.2	34.0	39.0	39.0	2070	37.7	36.2	39.2	39.2

Appendix Table 4.11: Sorghum biomass yield (t ha^{-1}) projected using ICHEC-EC-Earth climate model for different adaptation measures and time slices under RCP8.5

Year	PDo	PDo-15D	PDo+15D	PDo+15D+IR	Year	PDo	PDo-15D	PDo+15D	PDo+15D+IR
2017	29.6	25.6	33.4	33.4	2044	33.7	30.8	36.4	36.4
2018	31.2	27.6	34.8	34.8	2045	32.8	29.7	35.5	35.5
2019	31.5	28.3	34.3	34.3	2046	32.9	29.1	35.8	35.8
2020	32.2	28.3	35.0	35.0	2047	31.7	28.4	34.9	34.9
2021	30.5	26.6	33.3	33.3	2048	33.7	29.1	36.6	36.6
2022	30.2	26.9	33.1	33.1	2049	34.6	30.4	37.2	37.2
2023	29.4	25.2	33.2	33.2	2050	33.2	29.1	36.1	36.1
2024	30.7	25.9	34.3	34.3	2051	32.5	28.3	35.6	35.6
2025	30.5	26.7	33.6	33.6	2052	33.7	30.3	36.1	36.1
2026	32.7	29.3	35.3	35.3	2053	34.0	30.2	36.8	36.8
2027	34.1	30.7	36.1	36.1	2054	33.2	30.4	36.0	36.0
2028	32.7	28.3	35.5	35.5	2055	32.4	28.6	35.8	35.8
2029	31.9	28.7	34.7	34.7	2056	33.5	30.0	36.2	36.2
2030	31.4	27.7	34.2	34.2	2057	35.2	31.6	37.5	37.5
2031	30.9	26.9	34.2	34.2	2058	34.0	31.1	35.8	35.8
2032	31.0	26.5	34.3	34.3	2059	32.7	29.8	35.8	35.8
2033	32.8	29.9	35.4	35.4	2060	33.9	30.4	36.7	36.7
2034	31.9	28.5	34.6	34.6	2061	34.8	32.1	36.6	36.6
2035	34.3	31.2	36.3	36.3	2062	36.4	33.5	38.0	38.0
2036	31.6	27.7	34.5	34.5	2063	33.7	29.9	36.4	36.4
2037	32.0	27.9	35.2	35.2	2064	37.1	33.9	38.3	38.3
2038	32.1	28.6	35.4	35.4	2065	35.2	32.0	37.7	37.7
2039	31.3	27.5	34.8	34.8	2066	35.3	31.8	37.8	37.8
2040	32.0	27.9	35.5	35.5	2067	35.3	32.3	37.3	37.3
2041	31.2	27.7	34.5	34.5	2068	32.5	29.8	35.6	35.6
2042	32.2	28.3	35.2	35.2	2069	37.0	34.1	38.8	38.8
2043	31.1	27.3	34.4	34.4	2070	35.1	32.4	37.6	37.6

Appendix Table 4.12: Sorghum biomass yield (t ha^{-1}) projected using MOHC-HadGEM2-ES climate model for different adaptation measures and time slices under RCP4.5

Year	PDo	PDo-15D	PDo+15D	PDo+15+IR	Year	PDo	PDo-15D	PDo+15D	PDo+15+IR
2017	38.6	38.3	38.6	38.6	2044	39.5	39.4	39.5	39.5
2018	38.6	38.5	38.6	38.6	2045	39.5	39.5	39.5	39.5
2019	38.7	38.5	38.7	38.7	2046	39.5	39.4	39.5	39.5
2020	38.6	38.3	38.7	38.7	2047	39.5	39.4	39.5	39.5
2021	38.7	38.5	38.7	38.7	2048	39.6	39.5	39.6	39.6
2022	38.8	38.8	38.8	38.8	2049	39.6	39.6	39.5	39.5
2023	38.8	38.4	38.8	38.8	2050	39.6	39.4	39.6	39.6
2024	38.9	38.8	38.9	38.9	2051	39.6	39.2	39.6	39.6
2025	38.9	38.8	38.8	38.8	2052	39.6	39.6	39.4	39.4
2026	38.7	38.4	38.3	38.3	2053	39.7	39.6	39.6	39.6
2027	38.8	38.3	38.8	38.8	2054	39.7	39.5	39.7	39.7
2028	38.9	38.6	39.0	39.0	2055	39.7	39.5	39.7	39.7
2029	39.0	38.8	39.0	39.0	2056	39.7	39.5	39.7	39.7
2030	39.1	38.9	39.0	39.0	2057	39.7	39.6	39.7	39.7
2031	39.1	39.1	39.1	39.1	2058	39.7	39.6	39.7	39.7
2032	39.1	38.9	39.1	39.1	2059	39.7	39.5	39.6	39.6
2033	39.2	39.0	39.1	39.1	2060	39.7	39.6	39.7	39.7
2034	39.2	38.9	39.2	39.2	2061	39.7	39.4	39.7	39.7
2035	39.2	38.9	39.2	39.2	2062	39.7	39.6	39.8	39.8
2036	39.3	39.2	39.2	39.2	2063	39.8	39.7	39.8	39.8
2037	39.3	39.2	39.3	39.3	2064	39.8	39.7	39.8	39.8
2038	39.3	39.2	39.3	39.3	2065	39.8	39.7	39.6	39.6
2039	39.3	38.9	39.3	39.3	2066	39.8	39.8	39.8	39.8
2040	39.4	39.2	39.3	39.3	2067	39.7	39.4	39.8	39.8
2041	39.4	39.3	39.4	39.4	2068	39.8	39.7	39.8	39.8
2042	39.4	39.1	39.4	39.4	2069	39.8	39.5	39.8	39.8
2043	39.5	39.3	39.4	39.4	2070	39.8	39.6	39.8	39.8

Appendix Table 4.13: Sorghum biomass yield (t ha^{-1}) projected using MOHC-HadGEM2-ES climate model for different adaptation measures and time slices under RCP8.5

Year	PDo	PDo-15D	PDo+15	PDo+15+IR	Year	PDo	PDo-15D	PDo+15	PDo+15+IR
2017	38.6	38.1	38.6	38.6	2044	39.7	39.6	39.7	39.7
2018	38.6	38.0	38.7	38.7	2045	39.7	39.4	39.8	39.8
2019	38.7	38.2	38.7	38.7	2046	39.7	38.7	39.8	39.8
2020	38.6	37.9	38.8	38.8	2047	39.8	39.5	39.8	39.8
2021	38.8	38.6	38.8	38.8	2048	39.8	39.7	39.8	39.8
2022	38.9	38.5	38.8	38.8	2049	39.8	39.6	39.8	39.8
2023	38.9	38.4	38.9	38.9	2050	39.8	39.7	39.8	39.8
2024	38.6	38.0	38.9	38.9	2051	39.8	39.5	39.8	39.8
2025	39.0	38.7	39.0	39.0	2052	39.8	39.5	39.8	39.8
2026	39.0	38.6	38.9	38.9	2053	39.8	39.4	39.9	39.9
2027	38.8	37.8	39.1	39.1	2054	39.9	39.8	39.9	39.9
2028	39.1	38.7	39.2	39.2	2055	40.0	39.7	40.0	40.0
2029	39.0	38.2	39.2	39.2	2056	40.0	39.7	40.0	40.0
2030	39.2	39.1	39.2	39.2	2057	40.0	39.9	40.1	40.1
2031	39.3	39.1	39.3	39.3	2058	40.1	40.0	40.1	40.1
2032	39.3	39.1	39.3	39.3	2059	40.1	40.0	40.1	40.1
2033	39.2	38.3	39.4	39.4	2060	40.2	40.1	40.2	40.2
2034	39.4	38.8	39.4	39.4	2061	40.2	39.9	40.2	40.2
2035	39.4	39.2	39.4	39.4	2062	40.2	40.2	40.2	40.2
2036	39.4	38.8	39.5	39.5	2063	40.3	40.1	40.3	40.3
2037	39.5	39.1	39.5	39.5	2064	40.3	40.3	40.3	40.3
2038	39.6	39.4	39.6	39.6	2065	40.3	40.1	40.3	40.3
2039	39.6	39.2	39.6	39.6	2066	40.4	40.3	40.4	40.4
2040	39.6	39.3	39.6	39.6	2067	40.4	40.2	40.4	40.4
2041	39.5	39.0	39.6	39.6	2068	40.4	40.3	40.4	40.4
2042	39.7	39.5	39.7	39.7	2069	40.5	40.4	40.5	40.5
2043	39.7	39.4	39.7	39.7	2070	40.5	40.4	40.5	40.5

Appendix Table 4.14: Sorghum biomass yield (t ha^{-1}) projected using MPI-M-MPI-ESM-LR climate model for different adaptation measures and time slices under RCP4.5

Year	PDo	PDo-15D	PDo+15D	PDo+15D+IR	Year	PDo	PDo-15D	PDo+15D	PDo+15D+IR
2017	38.1	37.4	38.1	38.1	2044	39.4	39.1	39.4	39.4
2018	38.1	36.8	38.4	38.4	2045	39.2	38.6	39.5	39.5
2019	38.3	37.4	38.6	38.6	2046	39.1	38.5	39.4	39.4
2020	38.6	38.1	38.7	38.7	2047	39.5	39.1	39.5	39.5
2021	38.5	37.6	38.7	38.7	2048	39.5	39.2	39.5	39.5
2022	38.5	37.5	38.8	38.8	2049	39.5	39.0	39.6	39.6
2023	38.5	37.9	38.6	38.6	2050	39.6	39.2	39.6	39.6
2024	38.7	37.9	38.8	38.8	2051	39.1	38.4	39.5	39.5
2025	38.8	38.4	38.7	38.7	2052	39.5	39.2	39.4	39.4
2026	38.6	38.0	38.6	38.6	2053	39.3	38.5	39.5	39.5
2027	38.7	38.2	38.9	38.9	2054	39.5	39.0	39.6	39.6
2028	38.9	38.1	38.8	38.8	2055	39.6	39.4	39.7	39.7
2029	39.0	38.6	38.9	38.9	2056	39.5	39.2	39.6	39.6
2030	39.1	38.8	39.1	39.1	2057	39.6	39.1	39.6	39.6
2031	39.0	38.6	39.1	39.1	2058	39.7	39.5	39.7	39.7
2032	38.8	38.2	39.1	39.1	2059	39.4	39.0	39.4	39.4
2033	39.0	38.2	39.2	39.2	2060	39.7	39.6	39.6	39.6
2034	39.1	38.5	39.2	39.2	2061	39.7	39.4	39.7	39.7
2035	39.1	38.7	39.1	39.1	2062	39.8	39.7	39.7	39.7
2036	38.9	38.2	39.1	39.1	2063	39.6	39.2	39.8	39.8
2037	39.3	39.0	39.2	39.2	2064	39.4	38.8	39.6	39.6
2038	39.2	38.5	39.2	39.2	2065	39.7	39.3	39.8	39.8
2039	39.1	38.6	39.3	39.3	2066	39.2	38.4	39.5	39.5
2040	39.1	38.4	39.3	39.3	2067	39.7	39.1	39.8	39.8
2041	39.4	39.0	39.3	39.3	2068	39.6	39.0	39.7	39.7
2042	39.4	39.0	39.4	39.4	2069	39.8	39.6	39.8	39.8
2043	39.4	39.3	39.4	39.4	2070	39.7	39.1	39.7	39.7

Appendix Table 4.15: Sorghum biomass yield (t ha^{-1}) projected using MPI-M-MPI-ESM-LR climate model for different adaptation measures and time slices under RCP8.5

Year	PDo	PDo-15D	PDo+15D	PDo+15D+IR	Year	PDo	PDo-15D	PDo+15D	PDo+15D+IR
2017	38.6	38.6	38.5	38.5	2044	39.7	39.7	39.6	39.6
2018	38.7	38.4	38.7	38.7	2045	39.7	39.7	39.4	39.4
2019	38.7	38.7	38.5	38.5	2046	39.8	39.6	39.6	39.6
2020	38.6	38.7	38.2	38.2	2047	39.8	39.7	39.8	39.8
2021	38.7	38.8	38.3	38.3	2048	39.8	39.6	39.8	39.8
2022	38.9	38.7	38.7	38.7	2049	39.8	39.8	39.6	39.6
2023	38.6	38.7	38.1	38.1	2050	39.8	39.8	39.8	39.8
2024	38.5	38.5	38.1	38.1	2051	39.8	39.8	39.4	39.4
2025	38.8	38.8	38.6	38.6	2052	39.5	39.7	39.0	39.0
2026	39.0	39.0	38.8	38.8	2053	39.9	39.9	39.9	39.9
2027	38.7	39.0	38.2	38.2	2054	39.9	39.8	39.9	39.9
2028	38.9	39.1	38.5	38.5	2055	39.8	40.0	39.5	39.5
2029	39.2	39.0	39.1	39.1	2056	40.0	40.0	39.8	39.8
2030	39.2	39.1	39.0	39.0	2057	40.0	40.0	39.9	39.9
2031	39.3	39.3	39.2	39.2	2058	40.1	39.9	40.0	40.0
2032	39.1	39.3	38.5	38.5	2059	40.1	40.1	40.0	40.0
2033	39.2	39.3	38.9	38.9	2060	40.2	40.2	40.2	40.2
2034	39.4	39.4	39.3	39.3	2061	40.2	40.1	40.2	40.2
2035	39.4	39.3	39.4	39.4	2062	40.2	40.2	40.2	40.2
2036	39.5	39.5	39.2	39.2	2063	40.3	40.2	40.2	40.2
2037	39.4	39.3	39.1	39.1	2064	40.3	40.3	40.3	40.3
2038	39.5	39.5	39.3	39.3	2065	40.3	40.3	40.2	40.2
2039	39.3	39.5	38.6	38.6	2066	40.4	40.4	40.4	40.4
2040	39.6	39.5	39.6	39.6	2067	40.4	40.4	40.3	40.3
2041	39.6	39.6	39.5	39.5	2068	40.4	40.4	40.4	40.4
2042	39.7	39.6	39.6	39.6	2069	40.5	40.5	40.4	40.4
2043	39.7	39.4	39.7	39.7	2070	40.4	40.5	40.3	40.4

Appendix Table 4.16: Sorghum biomass yield (t ha^{-1}) projected using Multi Model Ensemble climate model for different adaptation measures and time slices under RCP4.5

Year	PDo	PDo-15D	PDo+15D	PDo+15D+IR	Year	PDo	PDo-15D	PDo+15D	PDo+15D+IR
2017	35.8	33.8	31.8	37.1	2044	37.6	36.1	35.1	38.7
2018	36.3	35.0	33.0	37.5	2045	37.5	35.9	34.3	38.4
2019	36.4	35.0	33.2	37.4	2046	37.8	35.9	34.4	38.7
2020	36.5	34.7	33.4	37.5	2047	37.1	35.7	33.7	38.3
2021	35.8	33.9	32.2	36.9	2048	38.0	36.3	34.8	39.0
2022	35.9	34.5	32.2	37.0	2049	38.1	36.5	35.4	39.0
2023	36.2	34.4	31.5	37.2	2050	37.9	36.4	34.6	38.8
2024	36.0	33.8	32.3	37.4	2051	37.4	35.4	34.0	38.5
2025	36.3	34.3	32.3	37.4	2052	38.0	36.8	34.8	38.6
2026	36.9	35.5	34.0	37.8	2053	37.9	35.8	35.2	39.0
2027	37.0	35.0	34.8	37.9	2054	37.6	36.2	34.9	38.7
2028	37.3	35.8	33.7	38.0	2055	37.5	36.2	34.1	38.6
2029	36.8	35.3	33.6	37.8	2056	37.9	36.4	34.9	38.8
2030	36.3	34.5	33.1	37.5	2057	38.2	36.6	36.0	39.1
2031	36.5	35.1	32.8	37.6	2058	38.1	36.8	35.2	38.8
2032	36.2	34.3	32.6	37.5	2059	38.2	37.1	34.6	39.0
2033	37.5	36.2	34.3	38.2	2060	38.2	36.8	35.3	39.2
2034	36.7	35.1	33.6	37.8	2061	38.0	36.5	35.9	39.0
2035	38.0	36.4	35.3	38.6	2062	39.0	37.5	37.0	39.6
2036	36.9	35.3	33.3	38.0	2063	38.3	36.6	35.1	39.2
2037	37.3	35.6	33.6	38.3	2064	39.3	38.2	37.4	39.7
2038	36.5	34.9	33.9	37.9	2065	38.7	37.5	36.3	39.6
2039	37.1	35.6	33.1	38.0	2066	38.5	37.1	36.3	39.5
2040	37.5	36.0	33.8	38.5	2067	39.0	37.9	36.3	39.6
2041	37.0	35.6	33.2	38.1	2068	38.3	37.4	34.6	39.2
2042	37.7	36.3	33.8	38.5	2069	39.5	38.5	37.6	40.0
2043	37.3	35.9	33.1	38.3	2070	38.7	37.8	36.4	39.6

Appendix Table 4.17: Sorghum biomass yield (t ha^{-1}) projected using Multi Model Ensemble climate model for different adaptation measures and time slices under RCP8.5

Year	PDo	PDo-15D	PDo+15D	PDo+15D+IR	Year	PDo	PDo-15D	PDo+15D	PDo+15D+IR
2017	35.8	33.8	37.1	37.1	2044	37.6	36.1	38.7	38.7
2018	36.3	35.0	37.5	37.5	2045	37.5	35.9	38.4	38.4
2019	36.4	35.0	37.4	37.4	2046	37.8	35.9	38.7	38.7
2020	36.5	34.7	37.5	37.5	2047	37.1	35.7	38.3	38.3
2021	35.8	33.9	36.9	36.9	2048	38.0	36.3	39.0	39.0
2022	35.9	34.5	37.0	37.0	2049	38.1	36.5	39.0	39.0
2023	36.2	34.4	37.2	37.2	2050	37.9	36.4	38.8	38.8
2024	36.0	33.8	37.4	37.4	2051	37.4	35.4	38.5	38.5
2025	36.3	34.3	37.4	37.4	2052	38.0	36.8	38.6	38.6
2026	36.9	35.5	37.8	37.8	2053	37.9	35.8	39.0	39.0
2027	37.0	35.0	37.9	37.9	2054	37.6	36.2	38.7	38.7
2028	37.3	35.8	38.0	38.0	2055	37.5	36.2	38.6	38.6
2029	36.8	35.3	37.8	37.8	2056	37.9	36.4	38.8	38.8
2030	36.3	34.5	37.5	37.5	2057	38.2	36.6	39.1	39.1
2031	36.5	35.1	37.6	37.6	2058	38.1	36.8	38.8	38.8
2032	36.2	34.3	37.5	37.5	2059	38.2	37.1	39.0	39.0
2033	37.5	36.2	38.2	38.2	2060	38.2	36.8	39.2	39.2
2034	36.7	35.1	37.8	37.8	2061	38.0	36.5	39.0	39.0
2035	38.0	36.4	38.6	38.6	2062	39.0	37.5	39.6	39.6
2036	36.9	35.3	38.0	38.0	2063	38.3	36.6	39.2	39.2
2037	37.3	35.6	38.3	38.3	2064	39.3	38.2	39.7	39.7
2038	36.5	34.9	37.9	37.9	2065	38.7	37.5	39.6	39.6
2039	37.1	35.6	38.0	38.0	2066	38.5	37.1	39.5	39.5
2040	37.5	36.0	38.5	38.5	2067	39.0	37.9	39.6	39.6
2041	37.0	35.6	38.1	38.1	2068	38.3	37.4	39.2	39.2
2042	37.7	36.3	38.5	38.5	2069	39.5	38.5	40.0	40.0
2043	37.3	35.9	38.3	38.3	2070	38.7	37.8	39.6	39.6

Appendix Table 4.18: Maize biomass yield (t ha^{-1}) projected using Multi Model Ensemble climate model for different adaptation measures and time slices under RCP4.5

Year	PDo	PDo-15D	PDo+15D	PDo+15D+IR	Year	PDo	PDo-15D	PDo+15D	PDo+15D+IR
2017	36.6	35.3	37.4	38.0	2044	30.9	32.0	31.4	38.9
2018	36.8	36.6	37.4	38.2	2045	30.0	31.8	30.8	39.1
2019	36.5	36.0	36.6	38.2	2046	36.7	37.1	35.7	39.1
2020	37.8	37.3	37.9	38.0	2047	32.0	31.8	32.3	39.0
2021	37.7	37.1	37.9	38.1	2048	32.0	31.7	32.4	39.2
2022	37.7	37.4	37.8	38.4	2049	38.4	38.2	38.0	39.1
2023	37.3	36.1	37.5	38.1	2050	31.3	30.7	31.7	39.2
2024	37.7	36.6	38.2	38.2	2051	27.7	29.6	25.4	39.3
2025	37.8	37.8	37.7	38.3	2052	31.8	32.4	31.8	38.8
2026	25.4	27.9	30.4	38.0	2053	24.2	25.1	23.0	38.9
2027	37.9	37.3	38.1	38.3	2054	39.0	38.4	39.1	39.2
2028	36.9	36.4	37.1	38.0	2055	35.0	35.0	37.5	39.3
2029	33.3	33.8	34.1	38.5	2056	30.1	27.7	35.2	39.4
2030	38.4	37.9	38.4	38.5	2057	27.7	24.2	28.6	39.0
2031	31.9	30.5	34.0	38.7	2058	29.2	29.9	30.7	39.3
2032	36.7	36.6	36.1	38.5	2059	26.9	26.9	26.9	38.8
2033	38.1	37.6	38.3	38.6	2060	31.8	33.4	31.1	39.3
2034	37.0	37.0	36.3	38.7	2061	33.3	33.3	34.4	39.3
2035	35.9	36.8	34.8	38.5	2062	28.5	28.4	29.9	39.4
2036	38.4	37.7	38.5	38.6	2063	36.8	34.9	38.4	39.4
2037	34.8	36.1	33.9	38.9	2064	30.7	30.1	30.9	39.4
2038	33.5	34.1	32.8	38.8	2065	35.4	34.8	36.7	39.2
2039	34.9	35.9	35.0	39.1	2066	35.8	36.3	36.4	39.3
2040	32.3	33.9	33.5	38.5	2067	37.6	33.7	38.8	39.4
2041	21.8	25.1	24.3	38.9	2068	32.0	31.8	37.4	39.3
2042	34.7	35.3	34.0	39.1	2069	34.9	34.0	34.8	39.3
2043	31.8	32.2	31.5	39.0	2070	36.7	33.8	36.3	39.2

Appendix Table 4.19: Maize biomass yield (t ha^{-1}) projected using Multi Model Ensemble climate model for different adaptation measures and time slices under RCP8.5

Year	PDo	PDo-15D	PDO+15D	PDo+15D+IR	Year	PDo	PDo-15D	PDO+15D	PDo+15D+IR
2017	37.2	38.4	37.2	37.2	2044	33.3	39.4	38.2	38.2
2018	37.4	38.5	37.7	37.8	2045	37.3	39.4	37.7	37.7
2019	36.0	38.5	35.8	35.9	2046	35.2	39.6	38.3	38.3
2020	37.0	38.3	36.1	36.1	2047	32.6	39.7	39.1	39.1
2021	37.0	38.4	35.8	35.8	2048	31.8	39.7	38.8	38.8
2022	37.1	38.6	37.0	37.0	2049	32.1	39.6	38.2	38.2
2023	37.2	38.2	36.6	36.6	2050	35.4	39.6	39.3	39.5
2024	34.8	38.1	36.2	36.2	2051	33.8	39.5	37.3	37.3
2025	37.5	38.4	37.6	37.6	2052	31.5	39.1	37.1	37.1
2026	36.3	38.7	36.9	37.2	2053	32.0	39.6	39.2	39.2
2027	36.8	38.2	36.6	36.8	2054	31.9	39.8	39.6	39.6
2028	35.0	38.6	36.3	36.3	2055	38.5	39.1	38.2	38.4
2029	37.8	39.0	38.1	38.1	2056	38.8	39.8	37.7	37.7
2030	37.5	38.9	37.4	37.4	2057	34.7	39.6	37.4	37.7
2031	37.8	39.1	37.3	37.3	2058	36.2	39.9	39.4	39.4
2032	37.6	38.6	35.9	35.9	2059	32.9	39.8	39.4	39.4
2033	37.5	38.9	37.6	37.8	2060	33.0	40.0	39.6	39.6
2034	36.0	39.2	37.5	37.5	2061	32.3	39.6	39.5	39.5
2035	35.7	39.3	38.1	38.1	2062	32.4	40.1	39.2	39.2
2036	29.9	39.2	37.0	37.0	2063	35.2	40.1	39.3	39.4
2037	38.3	39.1	36.9	36.9	2064	31.0	40.2	39.4	39.4
2038	33.9	39.3	37.7	37.7	2065	32.5	40.1	39.3	39.3
2039	32.5	38.4	36.4	36.4	2066	36.5	40.2	39.8	39.8
2040	35.2	39.5	38.8	38.8	2067	31.3	39.9	39.2	39.3
2041	34.0	39.5	38.4	38.4	2068	38.6	39.6	39.4	40.0
2042	37.4	39.2	38.4	38.5	2069	37.6	40.3	39.5	39.5
2043	31.7	39.1	38.7	39.3	2070	35.1	39.8	38.7	38.7

Appendix Table 4.20: Maize biomass yield (t ha^{-1}) projected using CNRM-CERFACS-CNRM-CM5 climate model for different adaptation measures and time slices under RCP4.5

Year	PDo	Pdo-15	Pdo+15D	Pdo+15D+IR	Year	PDo	Pdo-15	Pdo+15D	Pdo+15D+IR
2017	37.4	35.7	38.0	38.3	2044	37.3	35.5	38.6	38.6
2018	37.0	34.8	38.2	38.2	2045	37.7	35.8	39.0	39.0
2019	35.6	33.2	35.6	37.8	2046	37.6	35.2	38.7	38.8
2020	36.6	35.1	37.9	37.9	2047	37.5	35.8	38.8	38.8
2021	36.1	34.7	37.3	37.5	2048	35.2	34.8	33.5	39.1
2022	36.3	35.9	36.4	38.3	2049	37.8	36.0	39.0	39.0
2023	34.8	31.9	37.3	37.4	2050	37.2	34.8	37.6	38.9
2024	35.7	32.6	37.7	37.7	2051	38.1	36.4	37.9	39.1
2025	37.9	36.0	38.6	38.6	2052	37.7	35.5	38.7	38.9
2026	19.0	26.4	14.8	38.7	2053	19.1	21.6	14.5	38.7
2027	36.9	34.3	38.4	38.4	2054	38.2	36.5	39.2	39.3
2028	36.0	33.7	37.8	37.8	2055	38.5	37.4	39.3	39.3
2029	37.1	34.9	37.1	38.5	2056	38.0	36.3	36.4	39.2
2030	37.5	35.6	38.2	38.5	2057	32.7	34.1	28.9	39.3
2031	37.4	35.1	38.4	38.5	2058	37.2	35.5	38.7	38.8
2032	35.6	32.8	37.6	38.0	2059	38.1	36.6	39.0	39.2
2033	37.2	35.9	38.2	38.4	2060	34.7	35.7	34.4	39.2
2034	36.7	34.4	38.4	38.4	2061	37.7	37.1	36.2	39.3
2035	34.2	34.3	32.8	38.3	2062	36.6	36.1	34.8	39.2
2036	37.3	34.9	38.5	38.5	2063	37.9	35.7	39.2	39.2
2037	38.3	38.0	39.0	39.1	2064	36.6	37.6	36.3	39.6
2038	37.6	35.1	38.7	38.7	2065	37.6	36.2	38.5	39.1
2039	37.9	37.2	38.2	39.0	2066	32.8	33.9	32.4	39.4
2040	35.7	33.4	37.6	37.7	2067	38.3	36.6	38.3	39.3
2041	19.9	26.5	10.6	39.1	2068	37.5	35.7	38.9	39.0
2042	37.5	35.6	38.8	39.1	2069	37.0	35.0	36.0	39.0
2043	37.4	34.6	38.8	38.9	2070	37.9	36.4	39.0	39.2

Appendix Table 4.21: Maize biomass yield (t ha^{-1}) projected using CNRM-CERFACS-CNRM-CM5 climate model for different adaptation measures and time slices under RCP8.5

Year	PDo	PDo-15	PDo+15	Pdo+15+IR	Year	PDo	PDo-15	PDo+15	Pdo+15+IR
2017	37.9	36.8	38.4	38.4	2044	38.9	37.5	39.3	39.5
2018	37.1	36.4	38.1	38.4	2045	39.1	38.0	38.5	39.5
2019	32.6	34.6	32.6	38.4	2046	39.4	38.7	39.4	39.6
2020	36.2	36.4	37.2	38.5	2047	38.9	37.4	39.3	39.5
2021	37.4	35.7	38.1	38.1	2048	34.2	33.2	36.7	39.7
2022	37.6	36.2	38.4	38.4	2049	39.0	38.0	39.3	39.6
2023	38.4	37.9	38.6	38.7	2050	37.2	38.2	34.3	39.7
2024	**27.8**	31.4	**27.5**	38.7	2051	39.2	38.0	39.6	39.6
2025	38.5	37.4	38.8	38.8	2052	39.3	39.0	39.5	39.7
2026	32.7	34.7	32.9	38.8	2053	39.4	38.2	39.7	39.7
2027	35.3	36.4	36.0	38.8	2054	39.2	38.0	39.6	39.7
2028	**28.1**	31.9	26.6	39.0	2055	38.9	38.1	39.3	39.7
2029	38.1	37.0	38.6	38.6	2056	39.4	38.3	39.8	39.8
2030	37.9	36.0	38.8	38.8	2057	39.2	38.1	39.7	39.7
2031	38.2	36.7	38.9	38.9	2058	38.7	38.2	39.6	39.7
2032	38.3	36.4	39.0	39.0	2059	39.5	39.5	39.7	40.0
2033	39.1	38.7	39.2	39.2	2060	39.3	38.6	40.0	40.0
2034	36.3	36.6	38.1	39.1	2061	38.9	37.5	37.3	39.9
2035	39.2	38.7	39.3	39.3	2062	39.9	39.1	39.9	40.1
2036	**22.3**	28.7	**15.4**	39.2	2063	39.7	39.0	40.1	40.1
2037	39.2	38.4	39.3	39.3	2064	35.4	37.2	33.2	40.2
2038	37.9	35.8	38.9	39.0	2065	39.9	39.3	38.7	40.2
2039	38.7	38.4	37.9	39.3	2066	35.7	36.6	35.2	40.1
2040	39.2	38.7	39.4	39.5	2067	**19.1**	28.0	**11.3**	40.3
2041	38.3	37.4	39.4	39.4	2068	39.9	39.8	39.8	40.2
2042	38.9	38.0	38.9	39.5	2069	39.8	40.0	38.5	40.3
2043	39.0	38.4	39.4	39.5	2070	39.5	38.5	39.3	40.3

Appendix Table 4.22: Maize biomass yield (t ha^{-1}) projected using ICHEC-EC-Earth climate model for different adaptation measures and time slices under RCP4.5

Year	PDO	PDo-15	PDo+15	Pdo+15+IR	Year	PDO	PDo-15	PDo+15	Pdo+15+IR
2017	32.9	29.4	36.2	38.3	2044	31.7	34.1	32.6	39.1
2018	33.6	35.0	35.2	38.4	2045	27.4	30.6	32.8	39.3
2019	33.6	33.8	34.3	38.4	2046	38.8	38.0	39.1	39.2
2020	37.5	37.0	37.9	38.3	2047	38.8	37.7	39.0	39.3
2021	37.6	36.6	37.9	38.3	2048	37.6	38.0	38.0	39.3
2022	37.3	36.5	38.1	38.5	2049	37.1	38.2	35.2	39.4
2023	37.1	35.5	36.2	38.4	2050	36.7	36.2	37.9	39.3
2024	37.8	36.3	38.3	38.5	2051	17.1	22.2	11.2	39.4
2025	36.7	37.8	36.6	38.7	2052	35.4	37.4	36.6	39.4
2026	6.7	8.4	32.0	38.7	2053	26.2	25.8	26.1	39.3
2027	37.7	37.5	38.2	38.8	2054	39.1	38.7	39.1	39.5
2028	34.9	34.4	37.3	38.6	2055	39.2	38.7	39.3	39.5
2029	18.6	22.6	22.8	38.9	2056	24.1	21.8	31.2	39.5
2030	38.4	38.0	38.5	38.7	2057	22.3	7.1	32.0	39.6
2031	12.6	8.9	23.7	38.9	2058	26.7	27.2	33.1	39.5
2032	38.1	36.4	38.7	38.8	2059	8.5	13.0	6.6	39.5
2033	37.3	36.7	38.4	39.0	2060	37.1	38.3	37.5	39.5
2034	38.5	37.1	39.0	39.0	2061	39.3	38.7	39.5	39.5
2035	38.4	37.3	38.8	38.9	2062	21.2	24.9	18.2	39.5
2036	38.6	37.8	38.8	39.0	2063	35.8	35.9	37.0	39.6
2037	39.0	38.9	39.0	39.1	2064	34.7	30.4	37.5	39.6
2038	36.7	35.7	37.8	39.0	2065	27.9	29.1	30.8	39.5
2039	34.1	34.9	36.9	39.2	2066	32.0	33.1	35.5	39.6
2040	25.1	29.4	31.4	38.9	2067	39.4	38.7	38.7	39.6
2041	6.1	7.7	31.0	39.1	2068	12.6	17.2	32.5	39.6
2042	39.1	38.4	38.5	39.3	2069	23.9	24.8	24.8	39.6
2043	37.1	37.4	36.7	39.2	2070	31.0	33.5	28.8	39.6

Appendix Table 4.23: Maize biomass yield (t ha^{-1}) projected using ICHEC-EC-Earth climate model for different adaptation measures and time slices under RCP8.5

Years	PDo	PDo-15	PDo+15D	PDo+15D+IR	Years	PDo	PDo-15	PDo+15D	PDo+15D+IR
2017	34.6	31.3	36.6	36.8	2044	29.8	32.0	28.5	38.5
2018	35.7	32.6	37.4	37.6	2045	36.1	33.7	37.6	38.1
2019	35.2	32.7	36.7	36.9	2046	36.5	34.1	37.9	38.1
2020	35.6	33.1	36.9	37.2	2047	35.9	33.1	37.7	37.9
2021	34.2	31.7	35.8	36.1	2048	37.2	34.6	38.5	38.6
2022	34.1	31.5	35.8	36.1	2049	36.3	35.2	34.7	38.8
2023	34.3	31.0	36.3	36.6	2050	36.8	34.4	38.2	38.4
2024	35.3	32.0	37.0	37.2	2051	36.4	33.8	37.9	38.1
2025	34.6	31.8	36.4	36.6	2052	36.5	34.3	37.9	38.2
2026	35.9	33.8	37.2	37.4	2053	37.4	35.1	38.7	38.8
2027	35.4	34.5	35.9	37.7	2054	36.8	34.4	38.1	38.4
2028	35.2	33.5	36.7	37.6	2055	36.7	33.8	38.4	38.6
2029	35.3	32.9	37.0	37.3	2056	36.9	34.4	38.3	38.5
2030	34.6	32.4	34.1	36.8	2057	33.5	33.8	31.5	39.0
2031	35.1	32.3	36.9	37.2	2058	36.3	34.7	37.5	37.8
2032	35.2	32.1	36.9	37.1	2059	36.8	34.1	38.5	38.6
2033	35.9	33.8	37.4	37.8	2060	37.4	34.7	38.7	38.9
2034	35.4	33.0	37.0	37.2	2061	37.1	35.5	38.3	38.4
2035	36.7	35.1	37.7	37.8	2062	38.1	36.9	38.7	39.1
2036	35.3	32.6	36.9	37.1	2063	37.1	34.8	38.4	38.6
2037	36.0	33.4	37.6	37.7	2064	36.8	36.7	36.0	39.2
2038	36.3	33.5	37.9	38.1	2065	36.7	35.6	36.1	39.4
2039	35.8	32.8	37.6	37.9	2066	38.2	36.1	39.0	39.4
2040	36.4	33.3	37.8	38.1	2067	37.4	35.4	38.6	39.0
2041	35.5	32.5	37.4	37.6	2068	36.6	33.7	38.5	38.7
2042	35.9	33.4	37.5	37.8	2069	34.6	35.2	33.3	39.8
2043	35.4	32.5	37.2	37.4	2070	33.8	33.5	31.7	39.5

Appendix Table 4.24: Maize biomass yield (t ha^{-1}) projected using MOHC-HadGEM2-ES climate model for different adaptation measures and time slices under RCP4.5

Years	PDo	PDo-15	PDo+15	PDo+15+IR	Years	PDo	PDo-15	PDo+15	PDo+15+IR
2017	38.4	38.4	38.1	38.2	2044	15.4	19.2	15.8	39.3
2018	38.5	38.5	38.4	38.4	2045	15.9	21.8	12.7	39.3
2019	38.5	38.5	38.3	38.3	2046	31.0	36.1	26.0	39.2
2020	38.5	38.5	38.0	38.0	2047	12.6	14.3	13.0	39.2
2021	38.6	38.6	38.4	38.4	2048	15.8	14.7	19.1	39.4
2022	38.6	38.7	38.4	38.4	2049	39.3	39.4	38.9	38.9
2023	38.7	38.7	38.6	38.6	2050	11.8	12.6	11.8	39.4
2024	38.7	38.7	38.4	38.4	2051	16.1	20.8	13.5	39.5
2025	38.5	38.7	38.0	38.0	2052	15.2	17.5	13.3	38.4
2026	37.8	38.4	37.2	37.2	2053	12.2	13.6	12.5	38.9
2027	38.5	38.6	37.8	37.9	2054	39.4	39.0	39.2	39.3
2028	38.3	38.8	35.2	37.6	2055	22.5	24.6	31.8	39.2
2029	38.9	38.9	38.6	38.6	2056	19.0	13.2	34.2	39.5
2030	38.7	38.9	38.4	38.4	2057	16.6	16.2	15.0	38.6
2031	38.6	39.0	35.5	38.9	2058	14.4	19.2	12.2	39.5
2032	34.5	38.3	29.2	38.5	2059	22.2	18.7	24.3	38.6
2033	38.9	39.0	38.2	38.4	2060	16.0	20.0	13.5	39.6
2034	33.8	37.5	29.4	38.6	2061	16.8	17.8	23.1	39.4
2035	32.3	36.9	29.1	38.5	2062	16.6	13.0	27.3	39.5
2036	39.0	39.1	38.5	38.5	2063	34.0	28.5	38.4	39.4
2037	23.1	28.2	19.7	39.1	2064	12.2	13.3	11.1	39.6
2038	21.1	26.8	16.2	39.0	2065	36.7	34.3	38.2	38.6
2039	28.5	32.6	26.2	39.1	2066	39.3	39.0	39.0	39.3
2040	29.4	33.9	25.9	38.4	2067	33.1	19.8	38.7	39.6
2041	22.4	27.2	17.2	39.0	2068	38.7	34.8	39.3	39.6
2042	23.1	28.0	19.9	38.9	2069	39.1	36.4	39.1	39.5
2043	13.3	17.5	11.7	39.2	2070	38.3	26.1	39.0	39.4

Appendix Table 4.25: Maize biomass yield (t ha^{-1}) projected using MOHC-HadGEM2-ES climate model for different adaptation measures and time slices under RCP8.5

Years	PDo	PDo-15D	PDo+15D	PDo+15D+IR	Years	PDo	PDo-15D	PDo+15D	PDo+15D+IR
2017	38.4	38.4	38.1	38.1	2044	25.2	28.1	23.3	39.0
2018	38.4	38.5	38.1	38.1	2045	35.1	34.1	38.6	39.6
2019	38.5	38.6	38.2	38.2	2046	25.8	27.0	29.9	39.6
2020	38.6	38.5	38.4	38.4	2047	16.0	16.6	14.2	39.7
2021	38.7	38.7	38.6	38.6	2048	16.4	19.9	13.5	39.5
2022	38.6	38.7	38.1	38.1	2049	13.8	17.5	17.9	39.7
2023	38.7	38.7	38.4	38.4	2050	28.3	14.6	34.2	39.7
2024	38.8	38.6	38.4	38.4	2051	20.6	24.6	23.9	39.2
2025	38.9	38.9	38.7	38.7	2052	11.7	13.2	11.2	39.5
2026	38.6	38.8	37.8	38.2	2053	11.6	11.8	11.7	39.8
2027	38.9	38.7	37.2	38.7	2054	11.8	13.7	14.7	39.8
2028	39.0	39.0	38.9	38.9	2055	39.6	39.7	39.8	39.8
2029	39.0	38.9	37.4	38.8	2056	39.6	39.7	39.8	39.8
2030	39.1	39.1	39.0	39.0	2057	27.2	13.4	35.5	39.8
2031	39.1	39.1	38.9	38.9	2058	29.8	29.6	32.1	39.9
2032	39.2	39.2	37.1	39.1	2059	15.7	21.5	13.2	40.0
2033	36.6	39.0	31.4	39.2	2060	15.6	15.8	29.6	39.9
2034	33.7	38.3	28.4	39.1	2061	13.8	16.3	26.2	40.1
2035	27.7	33.7	22.0	39.0	2062	11.7	12.4	11.1	40.1
2036	23.5	29.5	18.5	38.8	2063	24.2	23.8	23.4	40.2
2037	39.4	39.3	39.3	39.3	2064	11.8	12.9	11.8	40.1
2038	22.7	29.0	17.1	39.3	2065	13.6	12.9	20.3	40.2
2039	17.6	22.9	15.4	39.3	2066	31.7	27.2	36.3	40.2
2040	26.0	31.3	22.8	39.3	2067	29.2	13.5	38.6	40.3
2041	22.8	26.9	20.3	39.5	2068	38.6	34.7	39.8	40.3
2042	35.9	38.5	35.7	39.3	2069	35.8	21.2	39.6	40.3
2043	13.9	18.0	11.9	39.6	2070	27.2	17.8	36.6	40.4

Appendix Table 4.26: Maize biomass yield (t ha^{-1}) projected using MPI-M-MPI-ESM-LR climate model for different adaptation measures and time slices under RCP4.5

Year	PDo	PDo-15D	PDo+15D	PDo+15+IR	Year	PDo	PDo-15D	PDo+15D	PDo+15+IR
2017	37.8	37.9	37.3	37.3	2044	39.2	39.3	38.7	38.8
2018	38.2	38.1	37.8	37.8	2045	39.0	39.1	38.7	38.8
2019	38.5	38.3	38.2	38.2	2046	39.3	39.0	39.0	39.0
2020	38.4	38.5	37.8	37.8	2047	38.9	39.2	38.4	38.4
2021	38.4	38.4	38.1	38.1	2048	39.3	39.4	38.9	38.9
2022	38.6	38.3	38.3	38.3	2049	39.4	39.4	39.0	39.0
2023	38.4	38.4	38.0	38.0	2050	39.4	39.4	39.3	39.4
2024	38.7	38.6	38.3	38.3	2051	39.4	39.1	39.2	39.2
2025	38.3	38.6	37.5	37.7	2052	39.0	39.3	38.6	38.6
2026	38.3	38.5	37.6	37.6	2053	39.2	39.2	38.7	38.7
2027	38.6	38.6	38.2	38.2	2054	39.3	39.4	38.7	38.8
2028	38.5	38.7	37.9	37.9	2055	39.5	39.5	39.5	39.5
2029	38.5	38.8	37.9	37.9	2056	39.2	39.4	38.9	39.2
2030	38.9	38.9	38.6	38.6	2057	39.4	39.5	38.4	38.4
2031	38.9	38.9	38.6	38.6	2058	38.6	37.7	38.6	39.5
2032	38.8	38.7	38.7	38.8	2059	38.8	39.1	37.9	37.9
2033	39.0	38.9	38.5	38.5	2060	39.4	39.6	38.9	38.9
2034	39.0	39.0	38.5	38.6	2061	39.5	39.6	38.9	39.1
2035	38.6	38.9	38.2	38.2	2062	39.5	39.6	39.2	39.3
2036	38.8	38.8	38.3	38.3	2063	39.5	39.5	39.3	39.3
2037	38.8	39.1	38.1	38.5	2064	39.3	39.3	38.9	38.9
2038	38.6	38.9	38.3	38.5	2065	39.6	39.6	39.5	39.5
2039	39.0	39.0	38.7	39.0	2066	39.2	39.2	38.8	38.8
2040	39.1	39.0	38.9	38.9	2067	39.6	39.6	39.3	39.3
2041	39.0	39.2	38.5	38.5	2068	39.3	39.4	38.8	39.0
2042	39.2	39.3	39.0	39.0	2069	39.6	39.6	39.4	39.4
2043	39.2	39.3	38.6	38.6	2070	39.5	39.5	38.7	38.7

Appendix Table 4.27: Maize biomass yield (t ha^{-1}) projected using MPI-M-MPI-ESM-LR climate model for different adaptation measures and time slices under RCP8.5

Year	PDo	PDo-15D	PDo+15D	PDo+15D+IR	Year	PDo	PDo-15D	PDo+15D	PDo+15D+IR
2017	38.1	38.4	37.2	37.2	2044	39.2	39.4	38.2	38.2
2018	38.4	38.5	37.7	37.8	2045	38.8	39.4	37.7	37.7
2019	37.7	38.5	35.8	35.9	2046	39.2	39.6	38.3	38.3
2020	37.6	38.3	36.1	36.1	2047	39.5	39.7	39.1	39.1
2021	37.6	38.4	35.8	35.8	2048	39.5	39.7	38.8	38.8
2022	38.1	38.6	37.0	37.0	2049	39.2	39.6	38.2	38.2
2023	37.6	38.2	36.6	36.6	2050	39.2	39.6	39.3	39.5
2024	37.6	38.1	36.2	36.2	2051	38.9	39.5	37.3	37.3
2025	37.9	38.4	37.6	37.6	2052	38.4	39.1	37.1	37.1
2026	38.1	38.7	36.9	37.2	2053	39.5	39.6	39.2	39.2
2027	37.6	38.2	36.6	36.8	2054	39.8	39.8	39.6	39.6
2028	37.8	38.6	36.3	36.3	2055	38.7	39.1	38.2	38.4
2029	38.8	39.0	38.1	38.1	2056	39.2	39.8	37.7	37.7
2030	38.5	38.9	37.4	37.4	2057	38.8	39.6	37.4	37.7
2031	38.7	39.1	37.3	37.3	2058	39.8	39.9	39.4	39.4
2032	37.7	38.6	35.9	35.9	2059	39.7	39.8	39.4	39.4
2033	38.4	38.9	37.6	37.8	2060	39.9	40.0	39.6	39.6
2034	38.8	39.2	37.5	37.5	2061	39.6	39.6	39.5	39.5
2035	39.1	39.3	38.1	38.1	2062	39.8	40.1	39.2	39.2
2036	38.6	39.2	37.0	37.0	2063	39.7	40.1	39.3	39.4
2037	38.5	39.1	36.9	36.9	2064	40.0	40.2	39.4	39.4
2038	38.9	39.3	37.7	37.7	2065	39.9	40.1	39.3	39.3
2039	37.9	38.4	36.4	36.4	2066	40.2	40.2	39.8	39.8
2040	39.4	39.5	38.8	38.8	2067	39.5	39.9	39.2	39.3
2041	39.2	39.5	38.4	38.4	2068	39.3	39.6	39.4	40.0
2042	38.9	39.2	38.4	38.5	2069	40.2	40.3	39.5	39.5
2043	38.6	39.1	38.7	39.3	2070	39.7	39.8	38.7	38.7

Appendix Table 4.28: Deterioration index data

Land Use	Depth	%OC	%N	Deterioration index		Mean deterioration index		
				%OC	%N	CL	GL	CA
CL	0-20	1.86	0.13	-68.41	-76.92	-69.39	-51.91	-43.17
	20-40	1.63	0.10	-63.20	-69.86			
	40-60	1.15	0.09	-71.84	-66.07			
GL	0-20	2.55	0.21	-56.68	-61.54			
	20-40	2.23	0.23	-49.65	-32.88			
	40-60	1.68	0.13	-58.93	-51.79			
CA	0-20	3.39	0.28	-42.35	-48.72			
	20-40	2.89	0.21	-34.66	-39.73			
	40-60	2.01	0.15	-50.73	-42.86			
FL	0-20	5.88	0.55					
	20-40	4.43	0.34					
	40-60	4.08	0.26					