

Climate Change and Variability Impacts on Agricultural Productivity and Food Security

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Abstract

Climate change is a real natural phenomenon. It is affecting agricultural productivity, especially in rain-fed agriculture. This paper provides comprehensive review studies on the impacts of climate change on crop and water productivity, soil water balance and food security. Global total annual anthropogenic GHG emission was grown by 70% between 1970 and 2004. The IPCC developed four emission scenarios or storylines, A1, A2, B1 and B2 and three groups of family storylines of A1FI, A1T and A1B. Climate predictions indicate a warmer world within the next 50 years, maximum and minimum temperatures increasing causing substantial yield decrease in low latitude areas; whereas, projected rainfall has no distinct variability pattern. By 2080, arid and semi-arid lands in Africa will increase by 5% to 8%. Global Climate Change Models (GCMs) have been used for different climate change impact assessment; however, due to lack of accuracy at local or smaller spatial simulation capacity; regional climate modeling, are being used to downscale climate scenarios at local and smaller scale around the world. Therefore, identifying and assessing suitable adaptation and mitigation practices have paramount importance and contributions to improve crop productivity, reduce the negative impacts of climate change on water availability and productivity. Global and regional climate models have been used as decision support tools for climate change impact assessment, and hence, application of such models to generate present and future climate data outputs for crop modeling and climate change impact assessment on crop production, water balance and food security is very essential.

Keywords: Climate change; Crop productivity; Water productivity; Soil water balance; Food security

Introduction

Climate change is a real natural phenomenon on the Earth. It has been a big concern since it affects agriculture, water availability, market and natural resources on the Earth. Agriculture is a complex and sensitive sector, where climate, management factors, market and technology play an important role on the productivity and profitability of the field. Climate is the primary determinant of agricultural productivity [1]. Climate change in IPCC usage refers to a change in the state of the climate that can be identified by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer [2]. Climate change is real where its first impacts are already being felt [3]. Climate change is expected to influence crop and livestock production, hydrologic balances, input supplies and other components of agricultural systems [1]. In developing and developed countries, risks from extreme climate impacts reveal higher levels of vulnerability with higher confidence on projected increases in droughts, heat waves and floods [2].

Understanding climate change impacts the livelihood of human beings, animals and the whole natural resource disturbances, application of suitable climate change adaptation and mitigation strategies are of paramount. Global total annual anthropogenic GHG emissions have grown by 70% between 1970 and 2004 [2]. Sustainable climate change adaptation and mitigation options have paramount importance in reducing the impacts of climate change on natural resources, crop production and food security. Plant breeding,

biotechnology, and conservation agriculture are important strategies in climate change adaptation [4]. This paper has been prepared to provide a comprehensive understanding on climate change and variability impacts on crop productivity and food security, and explore the factors under playing.

Emission Scenarios and Climate Models

Emission scenarios

Scenarios are alternative images of how the future might unfold and are an appropriate tool with which to analyze how driving forces may influence future emission outcomes and to assess the associated uncertainties [5]. Climate change scenarios include; higher temperatures, changes in precipitation, and higher atmospheric CO₂ concentrations [1]. The main driving forces of future greenhouse gas trajectories will continue to be demographic change, social and economic development, and the rate and direction of technological change [5].

In 1996, the IPCC began the development of a new set of emissions scenarios, effectively to update and replace the well-known IS92 scenarios. The approved new set of scenarios is described in the IPCC Special Report on Emission Scenarios (SRES). Four different narrative storylines were developed to describe consistently the relationships between the forces driving emissions and their evolution and to add context for the scenario quantification [5]; and the four scenarios storylines and the three A1 scenario families are described as below.

A1 scenario: The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income.

The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B) (where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end use technologies).

A2 scenario: The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than other storylines.

B1 scenario: The B1 storyline and scenario family describes a convergent world with the same global population, that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.

B2 scenario: The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with continuously increasing global population, at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the A1 and B1 storylines. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels.

According to the IPCC 2007 projected climatic scenarios under the different storyline and scenario families relative to 1989-1999 are described in Table 1.

Case	Temperature change (°C at 2090-2099 relative to 1980-1999)		Sea level rise (m at 2090-2099 relative to 1980-1999)
	Best estimate	Likely range	Model-based range excluding future rapid dynamical changes in ice flow
Constant year 2000 concentrations	0.6	0.3-0.9	Not available
B1 Scenario	1.8	1.1-2.9	0.18-0.38
A1T Scenario	2.4	1.4-3.8	0.20-0.45
B2 Scenario	2.4	1.4-3.8	0.20-0.43
A1B Scenario	2.8	1.7-4.4	0.21-0.48
A2 Scenario	3.4	2.0-5.4	0.23-0.51
A1F1 Scenario	4	2.4-6.4	0.26-0.59

Table 1: Projected climatic scenarios under different storyline and scenario families. Source: IPCC (2007).

Climate change predictions indicate a warmer world within the next 50 years, however, impact of rising temperatures on rainfall distribution patterns in the semi-arid tropics (SAT) of Africa and Asia remains far less certain. Impact of climate change has been assessed for the present and future. It has been indicated that there will be a climate change variability in the future (2030 and 2050) which will have a substantial impact on crop growth and productivity [6,7]. For example, studies on climate change projection in at different sites in Ethiopia indicate that there is an increase in maximum and minimum temperature in the future [6,7].

Future climate will depend on committed warming caused by past anthropogenic emissions, as well as future anthropogenic emissions and natural climate variability. So, sea surface temperature is projected to rise over the 21st century under all emission scenarios; with global mean surface temperature change for the period 2016-2035 relative to 1986-2005 is similar for the four RCPs and will likely in the range of 0.3 to 0.70°C (medium confidence) and will rise to 1.80°C at 2090-2099 with best estimate relative to 1980-1999 at B1 scenario [2]. Generally, the major regional impacts, particularly in Africa are shown in Table 2.

Year	Impact
2020	Between 75 and 250 million of people are projected to expose to increased stress due to climate change
2020	In some countries, yields from rain-fed agriculture could be reduced by up to 50%. Agricultural production, including access to food. In many African countries projected to be severely compromised. This would further adversely affect food security and exacerbate malnutrition

21 century	Towards the end of the 21 st century, projected sea level rise will affect low lying coastal areas with large populations. The cost of adaptation could amount to at least 5% to 10% of GDP
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Table 2: Climate change impact in Africa [2].

Global circulation models (GCMS) and regional climate models (RCMS) and their applications

Global Circulation Models (GCMs) are computer-based mathematical representations of the Earth's climate system in three dimensions as it evolves in time, based on the physical properties, interactions and feedback processes of the climate. In other words, GCMs, numerical models representing physical processes of the atmosphere, ocean, cryosphere and land surface, are the most advanced tools currently available for simulating the response of the global climate system to increasing greenhouse concentrations.

GCMs depict the climate using a three-dimensional grid over the globe, typically having a horizontal resolution of between 250 km and 600 km, 10 to 20 vertical layers in the atmosphere and sometimes as many as 30 layers in the oceans concentrations.

Due to the lack of accuracy in simulating site-specific physical and biological processes, Regional Climate Models (RCMs) have been used to fulfill the limitations of GCMs. Regional downscaling methods are used to provide climate information at the smaller scales need for many climate impact studies, and there is high confidence that downscaling adds value both in regions with highly variable topography and for various small-scale phenomena, inheriting biases from the global models used to provide boundary conditions [8].

RCMs vary based on their numerical, physical and technical aspects; however, the most commonly used RCMs in climate change downscaling studies are the US Regional Climate Model v.3 (RegCM3), Canadian Regional Climate Model (CRCM), UK Met Office Hadley Centre's Regional Climate Model v.3 (HadRM3), German Regional Climate Model (REMO), Dutch Regional Atmospheric Climate Model (RACMO), and German HIRHAM, which combines the dynamics of the High Resolution Limited Area Model (HIRLAM) and European Center-Hamburg (ECHAM) models.

- Consistency with global projections: They should be consistent with a broad range of global warming projections based on increased concentrations of greenhouse gases. This range is variously cited as 1.4°C to 5.8°C by 2100, or 1.5°C to 4.5°C for a doubling of atmospheric CO₂ concentration (otherwise known as the "equilibrium climate sensitivity")
- Physical plausibility: They should be physically plausible; that is, they should not violate the basic laws of physics. Hence, changes in one region should be physically consistent with those in another region and globally. In addition, the combination of changes in different variables (which are often correlated with each other) should be physically consistent
- Applicability in impact assessments: They should describe changes in a sufficient number of variables on a spatial and temporal scale that allows for impact assessment. For example, impact models may require input data on variables such as precipitation, solar radiation, temperature, humidity and wind speed at spatial scales ranging from global to site and at temporal scales ranging from annual means to daily or hourly values

- Representative: They should be representative of the potential range of future regional climate change. Only in this way can a realistic range of possible impacts be estimated
- Accessibility: They should be straightforward to obtain, interpret and apply for impact assessment

Climate Change Impacts on Crop Productivity

According to the IPCC 2007 report, in Africa, by 2020 between 75 and 250 million people are projected to be exposed to increased water stress, and due to low adaptive capacity in the region, the agricultural sector will be severely affected by climate change, where some crop yield from rain-fed agriculture could be reduced by up to 50%; and this would further cause food insecurity and malnutrition [2]. Understanding and identifying factors exacerbating climate change impacts on agriculture and other sectors, and make climate change adaptation and mitigation strategies, availability of climate data for decision and policy making is of paramount importance. However, availability of weather data and the format the data are available for their widespread use, has been a serious constraint to conduct applied researches in the field of agriculture, especially in developing countries. According to Hostler widespread interest in understanding past, present and future climate change and variability, and the response and feedbacks of natural and managed ecosystems has motivated the development and application of models and techniques to provide climate data at relevant spatial and temporal scales.

Crop productivity is projected to increase slightly at mid to high latitude for local mean temperature increases (1°C to 3°C), however, in low tropical and dry areas, crop productivity is projected to decrease with increase in temperature 1°C to 2°C [2]. Crop production in Ethiopia is mainly dependent on rainfall as a source of moisture for growth of crops, with irrigation contributing 1.1% of the total cultivated land in the country where the amount and temporal rainfall distribution are prominent for crop production [9,10]. Crop production under rainfed conditions is prone to variability in precipitation resulting in yield failure.

Climate-related hazards affect poor people's lives directly through impacts on livelihoods, reduction in crop yields, or the destruction of homes; and indirectly through, for example, increased food prices and food insecurity. In dry areas it is obvious that water, not land, limits agricultural production and that improving water use efficiency and decreasing demand must be major factors in the coping and adaptive strategies for climate changes; providing that, changes in climate patterns have the most acute effect on peoples living in the world's dry areas and marginal lands [11].

As temperature increases, the efficiency of photosynthesis increases to a maximum and then falls, while the rate of respiration continues to increase more or less up to the point that a plant dies [12].

Mean annual minimum temperature and annual rainfall variability and trend over Ethiopia in the period since 1951-2006; with annual minimum temperature increase about 0.37°C every ten years [13]. According to the Ethiopian meteorological agency, projected mean

annual temperature in 2030, 2050 and 2080 under the A1B emission scenario, will increase in the range of 0.9°C to 1.1°C, 1.7°C to 2.1°C and 2.7°C to 3.4°C respectively compared to 1961-1990 normal, with the small increase in annual precipitation [13].

Studies indicate that crop productivity under future climate projections is expected to be affected by climate variability in the future [6,7]. Minimum and maximum temperature and precipitation variability in the future climate will affect crop production, supply, and prices.

Climate Change Impacts on Crop Water Availability and Productivity

Climate change will affect water resources through its impact on the quantity, variability, timing, form, and intensity of precipitation.

Water productivity: is the ration of the net benefits from the crop, forestry, fishery, livestock, and mixed agricultural systems to the amount of water required to produce those benefits. Water productivity is a concept which can be defined as the amount of harvestable yield per unit of water consumed. In the essence, water productivity stands for producing more yields per unit of water applied under existing management and climate change scenarios. Climate change projections indicate that there will be an increase in water demand with the increasing population. Globally, the water required to feed the world in 2050 would be an increase of 4500 km³/year from the current 7000 km³/year; so, water productivity improvements can

effectively address food insecurity and poverty alleviation [14]. According to Falkenmark improving water productivity for food production greatly reduces the deficit water by 2000-3000 km³/year, and similar estimates by SEI indicate that water productivity improvements could reduce the future water demands (water addition needs) by 2200 km³/year [15].

According to Rockström, Barron, and Fox increasing water productivity in arid and semi-arid areas and sub-humid tropics can be achieved through improving and maximizing crop water availability, maximizing water uptake of plants and use of supplementary irrigation [16]. An efficient and well planned based on the crop water requirement, of supplemental deficit irrigation, enhances crops' water use efficiency, stabilizes yield by reducing crop failure in areas where moisture stress and erratic rainfall patten prevail. Rainwater harvesting, spate irrigation, conservation tillage, and supplemental irrigation are important climate change adaptation strategies for improved water productivity in arid and semi-arid areas [16].

Rain-fed agriculture covers 80% of the world's farmland and two-third of global food production [17]. Rain-fed agriculture plays a critical role in food production, with 80% of the agricultural land worldwide which produces low crop yield levels and high on-farm water losses [16]. The major challenges for the rural communities representing up to 80% of the population in certain countries are to improve the productivity of the arable land and the availability of water resources.

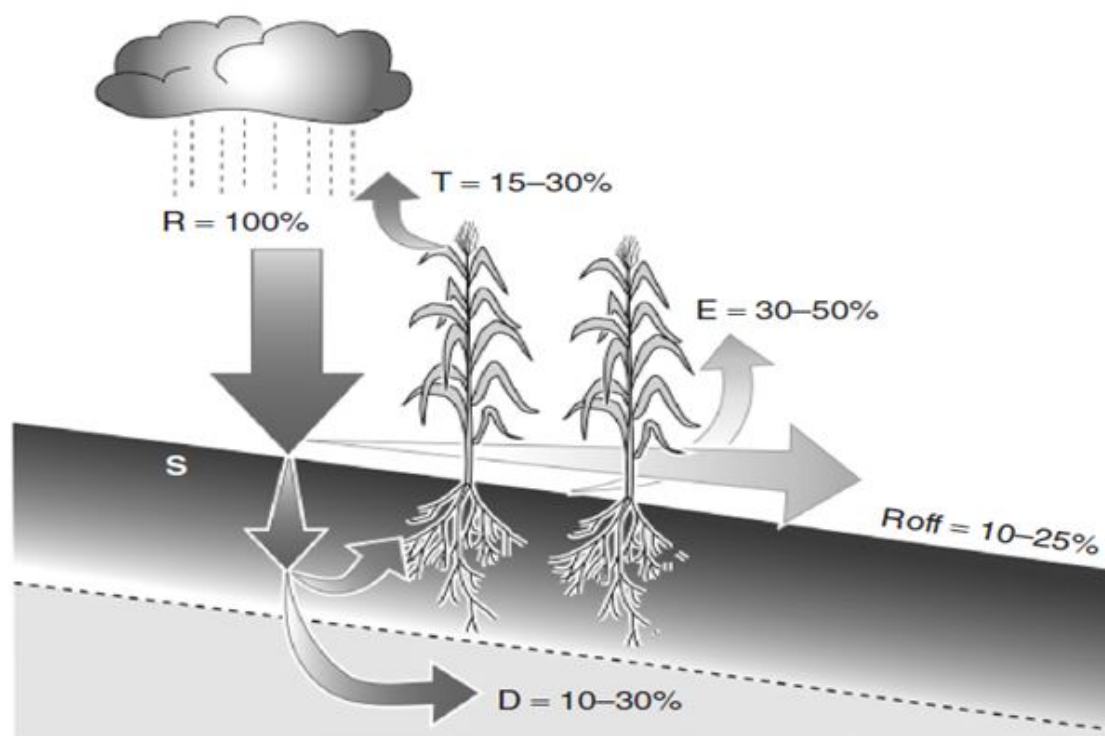


Figure 1: General overview of rainfall partitioning in farming systems in the semi-arid tropics of Sub-Saharan Africa. S: soil; R: rainfall; T: transpiration; E: evaporation; Roff: run off; D: drainage [16].

Under the circumstances, climate change influencing crop and water productivity, plant breeding has improved crop water productivity by increasing crop productivity; and hence, plant breeding (selection and producing suitable genotypes: high yielding and high water use efficiency) is an important climate change adaptation option, particularly for arid and semi-arid areas where recurrent soil moisture stress affects crop growth and productivity.

Climate Change Impacts On Crop Water Requirement

Climate change affects water balance, crop photosynthesis and crop growth either directly or indirectly by affecting directly the crop physiological processes or indirectly by affecting the different crop growth factors such as relative humidity, wind speed, soil temperature and atmospheric evaporative demand. Soil moisture balance; the influx and out-flux of water in the root zone can be quantified and simulated using a robust soil water balance model called Budget [18]. Crop models have the potential to quantify and simulate soil water balance under varying climate conditions and management practices; for example: the DSSAT crop model (soil water module) computes soil water processes including snow accumulation and melt, runoff, infiltration, saturated flow and water table depth, on a daily basis, and the FAO Aquacrop model is applied to simulate the soil water balance under irrigation and rain-fed conditions [18-20]. Similarly, the APSIM crop model computes and simulates soil water balance on a daily basis, with user-specified soil layers [21]. Water coming from either rainfall or irrigation is lost as evaporation and transpiration at the soil surface as shown in Figure 1. These models consider weather parameters that either directly or indirectly affects soil water balance; for example evaporation and transpiration rate of plants are directly affected by daily temperature variations, hence are required as input parameters to the models.

Climate change impacts on water balance will present changes in soil water storage, groundwater level, soil moisture level, soil moisture status and can provide some information about irrigation quality [22]. Climate change impacts on soil water balance will lead to changes of soil evaporation and plant transpiration, consequently, the crop growth period may shorten in the future impacting on water productivity [22]. Due to climate variability in the future climate projects, droughts and flood risks are expected [2], which may influence the regional soil water balance under various climatic conditions [22,23]. However, soil moisture impacts from climate change can be improved through tillage practices (zero and minimum tillage), planting deep-rooted crops, agroforestry practices and mulching and tie ridge [24].

Crop simulation models simulate the soil moisture dynamics under variable climatic, crop and management conditions. According to Allen soil moisture balance is determined as [25];

$$ETC = P + I - RO - DP + CR \pm \Delta S \text{ Equation (1)}$$

Soil water balance, depending on the temperature, rainfall and/or irrigation, soil type and crop water requirement (extraction pattern, ET, Kc, ETo), can be simulated or computed using the FAO Cropwat 8 [3]. The soil moisture flux in the root zone is affected by the aboveground environmental conditions (precipitation, RH, minimum and maximum temperature and solar radiation).

Climate Change Impacts on Food Security

Food security can be explained in many ways; however, it can be defined as to show its components. According to the FAO food security

is defined as 'a situation that exists when people have secure access to sufficient amounts of safe and nutritious food for normal growth, development, and an active and healthy life [3]. However, the major challenge of the 21st century is to achieve food security under marked shifts in climatic risks and with environmentally sound farming practices [26].

Agriculture, rural livelihoods, sustainable management of natural resources and food security are inextricably linked within the development and climate challenges of the twenty-first century [27]. Current climate risks and food insecurity intersect in the most vulnerable areas of the World; West Africa, East Africa, Southern Africa and South Asia. Climate change will affect all the dimensions of food security; food availability, food accessibility, food utilization, and food systems stability; impacting human health, livelihood assets, food production and distribution and market [3].

Food insecurity will continue to be a serious issue in coming decades, despite significantly projected hunger by the end of the century from the current 850 million to about 200-300 million, where many developing countries will experience serious poverty and food insecurity, due to localized high population growth rates, poor socio-economic capacity and continued natural resource degradation, with 40%-50% of all undernourished from Sub-Saharan Africa [28]. Food security is highly sensitive to climate risks in Ethiopia. According to the NMA the major adverse impacts of climate variability in Ethiopia include [13]:

- Food insecurity arising from the occurrence of droughts and floods
- The outbreak of diseases such as malaria, dengue fever, water-borne diseases (such as cholera, dysentery) associated with floods and respiratory diseases associated with droughts
- Land degradation due to heavy rainfall and
- Damage to communication, road and other infrastructures by floods

Conclusions and Recommendations

Climate change is a natural phenomenon affecting agriculture, natural resources, and food security. It is the main determinant of agricultural productivity; influencing crop and livestock production, hydrologic balances, input supplies, natural resources and other components of agricultural systems; with severe impacts in developing countries as a result of low adaptive capacity. It affects crop growth and yield, water availability, and productivity, soil water balance either directly or indirectly.

Global total annual anthropogenic GHG emission was grown by 70% between 1970 and 2004, while the prediction of future climate change indicates that there will be a warmer world within the next 50 years. Maximum and minimum temperature ranges projected to increase causing substantial yield decrease in low tropical and dry areas, whereas, projected rainfall patterns will have no distinct variability patterns.

Climate change predictions indicate a warmer world within the next 50 years. maximum and minimum temperature ranges projected to increase causing substantial yield decrease in low tropical and dry areas, crop productivity is projected to decrease with increase in temperature 1°C to 2°C [2]. Whereas, projected rainfall patterns will have no distinct variability patterns. By 2080, arid and semi-arid lands in Africa will increase 5% to 8%.

Agriculture, rural livelihoods, sustainable natural resources, and food security are inextricably linked within the development and climate challenges of the 21st century. To assist human predictions for climate change and variability, crop and climate models have been used as decision support tools. These models integrate agricultural and management factors and their biological and physiological processes. Therefore, these models enable to predict the impacts of climate change and variability in future climate scenarios under different emission scenarios and management practices. Climate change adaptation and mitigation strategies can be explored by analyzing and understanding the real climate change impacts for sustainable agricultural productivity and food security.

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