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Productivity Impacts of Climate Change on Ethiopia's Smallholder Farming System: A Review

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Abstract

The production of food in sub-Saharan Africa, which is severely hampered by the consequences of tropical climate change, depends heavily on smallholder farming practises. The system is in charge of feeding the entire population in Africa in general and Ethiopia in particular by producing around 90% of agricultural produce and farming 95% of the total area. This study examined how climate change has affected Ethiopia's smallholder farmers' productivity. The traits of smallholder farmers are described in terms of the size of the land, labour management, and scale of output, technology use, and climate risk adaption. The incremental temperature change over the years in Ethiopia, from 0.622 to 1.29 in 2000–2010 and from 1.37 to 1.507°C in 2020–2021, clearly shows the need to concentrate on climate change adaptation and mitigation policies that are especially smallholder-focused. Review papers also discussed the significant milk productivity disparity and the large agricultural production discrepancy in the nation. Smallholder farmers embrace technology at a very low rate; for instance, fertiliser with better seed utilisation is 4.58% and fertiliser with local seed is 4.76%. Technology adoption (resistant varieties and agronomic packages), crop diversification and cropping system, water harvesting and small-scale irrigation, integrated soil fertility management, crop-livestock mixed farming approach, and conservation agriculture are all examples of adaptation strategies that have been mentioned repeatedly in various papers. Building the capacity of smallholder farmers through the creation of climate-smart models is advised. Other recommendations include public investment in agricultural research and development to increase productivity, modelling of indigenous climate-smart conservation practises like those used by the Derashe people, and integrating crop-livestock-soil fertility management.

Keywords: Adaptation strategies; Smallholder characteristics; Temperature change; Water harvesting

Introduction

While the world's population has surpassed 8 billion and is rapidly growing, 130 people are born every minute. Agriculture faces significant challenges in addressing the daily hunger of nearly one billion people. As the average person in the globe becomes wealthier and consumes more food and meat [1- 4], food consumption patterns are shifting as a result of increased competition for land, water, energy, and other resources used in food production. Climate change poses additional challenges to agriculture, particularly in developing countries, where many current farming practices damage the environment. Agriculture, forestry, and other land use activities emit more than 10 billion tonnes of greenhouse gases, for example, 5 billion tonnes of CO_2 eq/yr from crop and livestock production, 4 billion tonnes of CO_2 eq/yr due to net forest conversion to other lands (a proxy for deforestation), 1 billion tonnes of CO_2 eq/yr from degraded peat lands, and 0.2 billion tonnes of CO_2 eq/yr by biomass fires.

Resource-poor producers, landless people, and marginalized communities are vulnerable to the negative impacts of climate change, which can be mitigated through adaptation, ranging from small changes in production practices to large-scale changes in farming and food systems. About 80% of the world's poor, who live in rural areas and are primarily farmers, can benefit from agriculture by increasing income, reducing poverty, and improving food security. Agriculture remains the main engine for economic growth, which accounts for 4% of global gross domestic products (GDP) with most sub-Saharan African (SSA) countries, contributing around 23% GDP by engaging 60% smallholder family and employing more than half of their total labor forc. Ethiopia is one of the country's most vulnerable to drought and flooding due to climate variability and change, which manifests itself as rising temperatures, reduced rainfall, increased rainfall variability, reduced crop yields, and food insecurity among low-income and agriculture-based economies [5,6]. The country's vulnerability to climate change and variability may be due to its reliance on climate-sensitive economic sectors such as subsistence crop cultivation and livestock production with low-capacitated smallholder farmers. This review, therefore, aims to assess the research findings and information on climate change effects on smallholder farming system productivity and food security.

Characteristics of the smallholder farming system

There are several definitions for a smallholder farming system based on the spatial context of the area. Smallholder farms in developed and developing countries, tropics, and latitudes differ in their farming characteristics. They are small-scale farmers, pastoralists, forest keepers, and fishers who manage about 80% of the farmland in sub-Saharan Africa and Asia.

Land size

The definition of smallholders primarily starts with their land tenure because 70% of the world's 570 million farms have less than a hectare of farmland. Farms of smallholders are generally small, often held under traditional or informal tenure, and are in marginal or risk-prone environments. Their land holding varies from less than one to

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10 hectares in Africa while >20 hectares in the USA. Other studies on the distribution of farmland in 81 countries show that 73% of farms are smaller than 1 hectare, 85% are smaller than 2 hectares and on average, 80% of holdings in 14 African nations are smaller than 2 hectares, including the European Union [7-10]. They also show that 50% of farms are smaller than 2 hectares in size and only use 2% of the total agricultural land. Around 25% of the world's arable land is utilised by these farms. The operating land holdings of smallholders in SSA, including Ethiopia, are less variable while the scarcity of land per farming family maintains highly variable with the average of 2 hectares and less than a hectare in densely populated areas which is decreasing from time to time in most of the world areas due to population growth.

Labor management

Smallholder production is largely dependent on household labor, with labor utilization per day varying widely on the relative resource constraints. Well-resourced farm families use about 96% of their farm operation, while resource-poor farm families employ labor to make daily food and family income. The labor demand of the family varies throughout the year and month depending on the working hours of the season. In Ethiopia, a large proportion of family members earn their income from labor rental in addition to non-farm activities that may determine the level of migration.

Production scale

Smallholder farming, which accounts for 70–80% of world food production, is often rain-fed, in which the only source of water used is from the sky. Rain-fed agriculture accounts for more than 95% of farmland in SSA, 90% in Latin America, 75% in the Near East and North Africa, 65% in East Asia, and 60% in South Asia. However, they produce a relatively small amount of food for their family and local consumption, which is generally the pillar of the country's economy in developing countries such as Ethiopia, and some of their commodities find the export market. On the other hand, dry land agriculture accounts for 40% of the world's total agricultural land and consumes one-third of the world's population. In Ethiopia, about 95% of food is from smallholders using rain-fed crop production systems.

Technology adoption and utilization

Technology adoption and utilization of smallholders are quite lower in African countries including Ethiopia. Level of education, age, and farmer-based organizations are significant influencers of technology adoption. For example, improved wheat variety adoption by farm households was determined by credit access, extension visits, soil fertility, plot size, off-farm employment, age of household head, distance from the input market, and farm experience in Ethiopia. Compared to the smallest commercial farmers, smallholders consume fewer technologies for production. Mostly smallholders operate their farm activities using limited resources and technologies. The five-year technology adoption rate in terms of crop area coverage indicates that the fertilizer and improved seed utilization package for barley, maize, Tef, wheat, and other major cereals is only 4.58%, while fertilizer for local seed is 4.74% in Ethiopia as indicated in.

Climate risk

Climate change and variability easily affect smallholder farming systems due to their low capacity to overcome the burden. Climate change affects the food production of smallholders in different ways in different areas of the world, and it's the most severe in developing countries, particularly SSA. Increasing temperatures in the tropics are challenging smallholder productivity, leading to increased water demand, reduced soil moisture, and water stress in many low-latitude areas, particularly in Africa. It reduces the total number of work hours for smallholder farmers by inducing heat stress which leads to the risk of unprotected outdoor work. Extreme heat stress can reduce plant photosynthetic and transpiration efficiencies and negatively impact plant root development, and flowering, which collectively can negatively impact yield. Floods, droughts, the spread of pests, and plant diseases, resulting in reduced livestock output and earnings, as well as high post-harvest crop losses affect smallholder farms, in particular, and everyone else in general.

Climate change and variability in Ethiopia

The definition of climate change and variability is well-presented in the supplementary material or PowerPoint presentation of this paper in the link Climate Change Effects on Smallholder Farming System Productivity in Ethiopia - Mendeley Data. Climate change, altering the composition of the national, regional, and global atmosphere, is any change of climate over time, whether due to natural variability or is attributed directly or indirectly to human activity. Climatic variability, deviation of climatic statistics over a given period of time in the frame of the month to a decade, is variations in the mean state and other statistics of the climate on all temporal and spatial scales, beyond individual weather events such as temperature, rainfall, the occurrence of extremes magnitude and rate of the climate change that causes the impacts on the area of public health, agriculture, food security, forest hydrology and water resources, coastal area, biodiversity, human settlement, energy, industry, and financial services. In Ethiopia, climate variability and change are mainly manifested through the variability and a decreasing trend in rainfall and an increasing trend in temperature , which shows large regional differences.

Ethiopia is vulnerable to natural and hydro-meteorological disasters, which are exacerbated by the country's high poverty rate and reliance on the key sectors most vulnerable to climate change: agriculture, water, tourism, and forestry. Recurrent droughts make the country extremely vulnerable, which is aggravated by the country's geographical diversity and highly marginalized population. Other non-climate-related stresses, such as the lack of infrastructure to accommodate population growth, have an impact on natural disasters and climate change vulnerabilities. According to the FAOSTAT database, the temperature change in the 30 years from 1961–1991, the highest temperature record was 0.824°C in 1988, while the lowest record was -0.5°C in 1968 and from 1992–2021 the lowest temperature increment record was 0.192°C in 1992 while the highest record was 1.565°C in 2016 and the temperature change up to 2021 is presented in. Rainfall is highly variable and very low in 1987, 1990, and 2009, and higher in 1997, 2007, and 2005, and in similar years higher minimum and maximum temperatures were recorded. The temperature annual change rate from 0.229 in 1986 to 0.382 in 1987 (66.28%) and 0.824 in 1988 was 115.71% and 524.2% from 1989 to 1990.

Rapid population growth poses high demand on limited water and rangeland resources. Between 2010 and 2020, according to UN population statistics, the population of Ethiopia, Kenya, and Somalia grew by about 30%, from 142 to 184 million (Reference/s). These regions were at an exceptional level of risk in the early 2022 cropping season, due to intense poverty, population growth, rising temperatures, poor rainfall, dying livestock, poor harvests, and extremely limited water resources. Such an exceptionally prolonged and persistent agro-pastoral drought sequence caused a disruptive humanitarian disaster. As a result, more than 6.8 million were under urgent humanitarian assistance in the same season. Lack of clean water (4.4 million in critical water shortages), malnutrition of more than 860,000 children, drop out of school for 155,000 children, and other disasters including displacement are the major effect of drought in 2022 in Ethiopia. Greenhouse gas emission in the country is also increasing from year to year .

Climate change effects on agricultural productivity in Ethiopia

Agricultural GDP

The agriculture sector in Ethiopia plays a great role in building the national economy and contributes 35.6% of the GDP. However, the sector is highly dependent on rainfall, as only 1% of all cultivated land is irrigated. Although the growth rate of the agricultural sector has been declining from 13.5% to 4.3% from 2005 to 2020, its contribution to the Ethiopian economy is still high. Climate change and variability are affecting the sector through crop failure due to erratic rainfall, low animal productivity due to the poor quality and quantity of feed supply, and soil erosion and land degradation. It is briefly discussed below in this paper for crop and livestock sector productivity in response to climate change in Ethiopia.

Major crop productivity

Smallholder farming systems are accountable for the bulk of Ethiopia's food production, cultivating over 90% of all arable land with poor soil fertility as a result of continuous cropping and little input of nutrients to replace removal at harvest and providing over 95% of agricultural production. Smallholder farmers commonly cultivate major cereals such as teff (*Eragrostis tef* [Zucc.] Trotter), maize (*Zea mays*), wheat (*Triticum aestivum*), barley (*Hordeum vulgare*), and sorghum (*Sorghum bicolor*). Root crops such as sweet potato *(Ipomoea batatas)*, potato (*Solanum tuberosum*), cassava *(Manihot esculenta)*, taro (*Colocasia esculenta*), and enset (*Ensete ventricosum*), which are also the major food security crops and commonly cultivating in the southern and southwest Ethiopia.

A total of 391 improved cereal varieties which comprised 36 tef, 66 maize, 35 rice (15 upland, 11 lowlands, and 9 irrigated), 106 bread wheat, 35 durum wheat, 47 sorghum, 53 barley (37 foods and 16 malts) and 13 finger millet have been released/registered in Ethiopia up to date. However, of particular note is the average yield difference of 2.8 t ha^{-1} in maize yield compared to the potential yield of 16.3 t ha^{-1} obtained in potential production limited by the photosynthetic efficiency of the crop. About 75% of the water-limited yield gap was reported for pulse crops in East Africa and also major cereal crop yields in smallholder farms were very low compared to their potential and the yield was less than 50% of experimental farms and research stations. The yield gap from the global yield gap atlas (GYGA) presented for major cereals and pulses are presented.

Such low crop yields can be attributed to poor input management (fertilizer, weeds management, etc.). Low soil fertility could ultimately affect food security, with a large amount of grain needing to be imported so that 30–50% of domestically consumed wheat was imported in the past due to a lack of production inside the country. The long-term climate effect, which means rising temperature, affects crop production by altering the crop growth cycle, which would likely lead to a decline in agricultural output. For example, each degree centigrade increase in temperature during the growing season of spring and winter wheat reduced the growing period by 12 days. Crop phenology, which plays an important role in annual carbon uptake during growth and senescence, will vary with increasing temperatures due to reduced crop yield and quality following climate changes.

Livestock productivity

Ethiopia has the largest livestock population in Africa and ranks fifth in the world in terms of cattle population next to Brazil, India, China, and the USA. However, milk productivity is much lower than in any of the countries compared. According to the central statistical agency, the total livestock population in Ethiopia is increasing from 193.23 to 251.19 million from 2018 to 2021, excluding beehives, with 70.3, 49.9, 52.5, 2.15, 10.8, 0.4, 8.15, and 56.99 million cattle, sheep, goats, horses, donkeys, mules, camels and poultry, respectively. The sector contributes significantly to the country's economy, accounting for 15–19% of total GDP, 35–40% of agricultural GDP, and 37–87% of household incomes. Due to Ethiopia's diverse agroecology, the sector uses a wide range of systems, from pastoralism to mixed crop-livestock farming with high levels of intensification.

Meat, milk, honey, eggs, cheese, and butter are examples of livestock products and byproducts from a smallholder mixed farming system (50% meat and 90% milk) that provide essential animal protein to improve people's nutritional status. Exports including live animals, hides, and skins play a crucial role in earning foreign currency. As shown in, draught animals provide the necessary power for smallholders to cultivate their land. They are also crucial modes of transportation for smallholders and their families to travel long distances, transport their agricultural products to markets, and bring back their daily needs. The highland's high animal density limits Ethiopian livestock's economic potential, but the crop-livestock mixed farming system does offer some protection in the event of crop failure because livestocks are a "near-cash" capital stock. Additionally, livestock produces farmyard manure, which is frequently used to improve soil fertility and is also used as a source of energy.

Climate change-induced heat stress reduces animal productivity and reproductive performance, directly affecting milk components and production, meat production, reproductive efficiency, and animal health. As a result, the sector has been facing frequent water shortages and feed supply in quality and quantity. In the coming decades, crops and forage plants will continue to be subjected to warmer temperatures, elevated carbon dioxide, as well as wildly fluctuating water availability due to changing precipitation patterns. Climate change can adversely affect productivity, species composition, and quality, with potential impacts not only on forage production but also on other ecological roles of grasslands. Agricultural livestock are responsible for a large proportion of global methane gas emissions. Therefore, understanding the trade-off between livestock number, overall farm size, and sustainable land production is crucial.

Land use and soil quality

The main problems with smallholder farmers' production in SSA have been low soil fertility and ineffective soil management. Under complex and diverse smallholder production systems, in the combination of plant and animal species exploited, the types of integration between them, the production objectives, and the institutional arrangements for managing natural resources are highly required. Arable land for crop production by smallholders competes for supplies of animal feed. Despite of its higher fodder quality, depletion, feeding of animals on crop residues has been affecting the soil fertility of smallholder farmers. Agricultural lands could be exposed to erosion and structure deterioration, which may affect the quality of soil due to unmanaged rearing and overgrazing of high livestock densities.

Continues farming, low nutrient use, low soil conservation practices, and inorganic farming could be the major problems of smallholder land use system, deteriorating the quality and reducing soil fertility. As reports of different scholars, the socioeconomic triggers of soil fertility status of smallholders are age of the farmer and livestock holding, education status and the slope of the land, family size and labor availability, and relative wealth of the smallholder farmer selling the organic manure after his lands. Furthermore, indigenous soil management practices for augmenting soil quality and crop productivity have been not well documented.

Climate change adaptation of smallholders through smart agricultural practices

Implementing new agricultural technologies

New crop varieties with special traits, which are released for drought tolerance, disease, and pest resistant, are important for yield compensation under climate change. The adoption of smallholder farmers of new crop varieties has been determined by marital status of the household head, access to credit, access to extension services, and farm income. Gender of household head and farm income had a positive influence on farmers' adoption of fertilizer and pesticide use. Improved crop varieties and livestock breeds with high adaptation to the environment can help offset declines in yields due to climate change and even significantly increase global production. Early maturing variety is prominent to shorten growing period from sowing to maturity which could escape the dry season temperature damage with increasing temperatures, reduces light interception, biomass accumulation and grain set, and consequently grain yield. Crop varieties are differently responding to temperature and require specific accumulated heat units for growth that varieties adapted to increased temperature delay maturity and extend grain filling requiring more heat units.

Cropping system and crop diversification

Cropping intensity affects crop yield differently under climate change. Compared to maize mono-cropping, the majority of cropping systems have neutral to positive effects on smallholder productivity, although the magnitude of the impact varies. Maize-legume systems are associated with a 17–38% increase in maize yields compared with maize mono-cropping. More diverse systems likely enable farmers to capture a combination of agronomic benefits in the soil, such as through phosphorus enhancement and nitrogen fixation, from a range of crops, which contributes to improved yields. The resilience of smallholder agricultural systems in SSA is ensured through crop diversification, especially the use of cereals and legumes, as a practical method of climate-smart agriculture. Smallholder farmers in Ethiopia have implemented crop diversification based on various socio-economic criteria, such as household head gender, educational attainment, access to extension services, market linkages, and others. Crop diversification has been studied in Ethiopia as increasing stability and risk-minimizing factors for smallholders under climate change. Moreover, other findings supporting farming diversification reveal that crop rotation and mixed cropping of different species in a farm by managing planting dates are the major climate adaptation strategies in South Africa.

Major driving forces for crop diversification for smallholder farmers include increasing income on small farm holdings, withstanding price fluctuation, providing resilience to highly variable weather conditions resulting from climate change, improving fodder for livestock animals, conservation of natural resources and minimizing environmental pollution, depending on crop rotation, decreasing insect pests, diseases, and weed problems, increasing community food security. Farms less than 2 hectares devote a greater proportion of their production to food and account for greater crop diversity, while large-scale farms have the greatest proportion of post-harvest loss.

Crop-livestock mixed farming

Integrated crop-livestock farming has been identified as a key parameter to adapt, depending on the age and family size, the amount of cultivated land and rainfall, climate change hazards, and improve food security in Ethiopian smallholders' situation. Milk produced from dairy improves the family's nutritional demand, the power of animals to manage small plots of land, animal manure improves the nutrient demand with low cost, and crops provide feed for livestock to improve productivity. The integration of the crop-livestock farming system compensates the smallholder farmer for dependency on rainfall and temperature-dependent crop production failure and improves the interdependency of the two sectors. In the mixed crop-livestock systems of Ethiopia's highlands, the dependency between household net positions in the crop and live animal markets was proven. However, households' net positions in the crop market have a stronger relative impact on their net position in the live animal market.

Integrated nutrient management

Managing 0.7 hectares of farmland in an integrated farming system approach, farmers gradually transitioned to sustainable family life in India and to fisheries in Vietnam. Soil and water conservation have been a key parameter to mitigate climate change that smallholder farmers are devoted to involve in soil and water conservation of both private and communal land. Low-cost gully rehabilitation is recommended for smallholder farmers to restore grasses and shrubs and improve the soil fertility status of arable lands. Conservation agriculture allows effective and efficient use of water, and other agricultural inputs to improve the food security of smallholder farmers in dryland areas. Application of integrated nutrients significantly improved barley yield in Ethiopia. Results of comparative performance of integrated nutrient management between composted agricultural wastes, chemical fertilizers, and bio-fertilizers in improving soil quantitative and qualitative properties and crop yields under arid conditions showed that recycling agricultural wastes into new productive composts and integrated nutrient management practices changes in soil properties and improves crop production under arid conditions.

Water harvesting and small-scale irrigation

Crop yield and quality are expected to be lower and more variable in most low-rainfall regions. In this regard, water harvesting technologies and management are crucial to the adaptation of smallholder farmers who mainly depend on rain-fed agriculture. Water conservation, water harvesting, and storage techniques for efficient utilization are important adaptation strategies at smallholder farm level. Conservation agriculture can also help both irrigated and rain-fed systems to increase the organic matter in the soil, improving moisture retention and water-use efficiency. Derashe is an area known for the problem of soil erosion and moisture stress, and to relieve the challenge, hundred-plus years ago, they innovated conservation agriculture with an indigenous mulching technique, locally known as *Targa-na-Potayta*. The technology helped to alleviate the drought and transform their livelihoods from government food subsidies to potential producers.

The scholars reported from their experiment with ***Targa-na-potayta*** indigenous soil and water conservation practice of Derashe people is significantly efficient in improving clay content to be 53.74 ±

2.68%, field capacity 47.8 ± 1.09%, water holding capacity 15.2 ± 0.37%, pH 8.02 ± 0.07, soil organic carbon 1.8 ± 0.02%, and exchangeable cations 68.2 ± 1.66 meq/100 g when comparing with the conventional tillage of other areas. ***Targa-na-potayta*** has been confirmed to be significantly higher in soil and water conservation and improves the yield of sorghum in arid and semi-arid agriculture. Agroforestry land use system is more efficient in improving soil fertility in terms of organic carbon, water stable aggregation, total porosity, total nitrogen, and microbial biomass carbon under smallholder farming systems than rain-fed cultivation and irrigated cropping.

Capacity building

Improving climate change awareness, facilitating the participation of female-led households in income generation, and strengthening existing adaptation measures improve the food security of smallholder farmers in rural areas of Ethiopia. Farmers' knowledge plays an important role in the adoption of new technologies such as improved seed and fertilizer package which requires strong and skilled extension support to improve the grain yield of some selected cereals.

Summary of the gaps identified and the way forward

In order to ensure the country's food security, the smallholder farming system in Ethiopia should be given special attention. This is mainly because the landholding of smallholders who need daily food could not be expanded, while the population depending on the similar land size is highly growing. The opportunities of a smallholder farming system are that they are having available labor, a large workforce, already practicing the integration of livestock rearing with crop production, yield gap (potential for increasing crop and livestock yield), crop diversification, and small-scale irrigation potential. However, the gaps identified in climate change adaptation of smallholder are technology adoption rate which is depending on access to extension services, age and sex of the family, head, farm experience in some cases, access to credit, level of education and income source or relative wealth level of the family. The technologies which could bring the development of smallholders from subsistence to self-sufficient in food and nutrition have to be intensified in a farm fragmented approach. Crop diversification with soil and water conservation strategies is an ideal approach to minimize risk. The number of animals each smallholder has is very limited, but still, it needs to be determined through a model-based technique to balance the crop-livestock-soil productivity to reduce soil fertility depletion. There is relatively little information on how crop-livestock interactions may be affected by changes in climate and climate variability. This is an important gap because these interactions may offer some buffering capacity to help smallholders adapt to climate change.

The way forward with high intentions are physical, conceptual, and financial capacity building of smallholders with access to climate and agricultural information; develop environmentally gentle climate smart models for ensuring the livelihood of smallholders, large focus on public investment in agricultural research and development to improve the productivity of smallholders, appreciating and modeling indigenous climate-smart conservation practices like in Derashe people, integration of crop-livestock-soil fertility management since they are not detached in smallholder level and off-farm activities for managing the free wage of smallholders to make family income and reduce migration. Additionally, in Ethiopia, there are fragmented studies about the system, and smallholder farming system analysis has to be performed by using secondary data, primary data, ArcGIS, system analysis model, and other appropriate tools to come up with a comprehensive sustainable solution.

Conflict of Interest

Authors have no conflict of interest

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