Journal of Cleaner Production 449 (2024) 141793

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Impacts of the changing climate on agricultural productivity and food security: Evidence from Ethiopia

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ARTICLE INFO

Handling Editor: Cecilia Maria Villas Bôas de Almeida

JEL classification:
C32
C33
Q18
Q54
Q58

Keywords:
Climate change implications
Mitigation and adaptation strategies
Agricultural productivity
Food security
Cobb douglas productivity function
Ethiopia

ABSTRACT

This study investigates the influence of climate change on agriculture productivity and food security in Ethiopia. We use 2011–2020 state level data set for four major seasonal crops of Cash and Food in Ethiopia, namely, barley, wheat, maize, and sorghum. Methodologically, we apply the productivity function and the Ricardian approaches in the modelling for simulating the association of climate change with agriculture productivity. This study documents the interconnectedness among changes in climate, security of food and agriculture, indicating how the prior changes bring the latter kind of alterations. In general, agriculture in Ethiopia is prone to changes in climate and variations in the levels of precipitation, posing threats to food security of the rural population. The specific findings of this study highlight sorghum and barley as the majorly impacted stable crops as a consequence of changes in meteorology. Furthermore, the study reports that barley production in particular makes vital contribution to causing food insecurity in Ethiopia. The study recommends some policy prescriptions and adaptation methods for mitigating the detrimental effects of climate change on agricultural production and food security in Ethiopia and similar agro-based economies at large.

1. Introduction

The consequences of climate change on agriculture have become a matter of grave concern for the global scientific community and scholars, pressure groups, governments, and policy makers (Kang et al., 2014; O'Neill et al., 2020; Prăvălie et al., 2020; Wang et al., 2023). Estimates reveal that impacts of climate change in the forms of drought and heavy rainfall will accelerate the soil erosion 10 to 100 times quicker than the time taken during its formation (Masson-Delmotte et al., 2018; Porter et al., 2014). Climatic impacts will also continue to distress the microbial inhabitants and affect their enzymatic functions in soil (Hendriks et al., 2022; Chai et al., 2022), fuelling unprecedented biodiversity loss (FAO, 2016). All these changes are increasingly affecting agriculture production and human systems worldwide (Fróna et al., 2021; Lamboll et al., 2011), posing threats to food security in most regions (Meyfroidt, 2017; Thornton et al., 2020; World Bank, 2013). Countries from the Global South are the most exposed to the detrimental consequences of climate change in the form of outright crop failure caused by the positive nexus between intensifying temperatures and plants' lowering growth phases (Abubakar and Dano, 2020; Ayers et al., 2014; Hasan et al., 2020; Hossain et al., 2019), chronic famines and severe desertification from climate change (Besada and Werner, 2015; Chowdhury et al., 2022; Donkor et al., 2019), mostly in tropical latitudes (FAO, 2017; Filho et al., 2022). Given this backdrop, "finding the right balance between food and nutritional security, protecting the environment and addressing climate change remain major challenges for sustainable food systems and the use and management of land and water" (Grote et al., 2021, p. 2). Addressing the global climate impacts are gradually evolving into a challenge for all countries in achieving the associated Sustainable Development Goals (SDGs) (Rahman et al.,

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https://doi.org/10.1016/j.jclepro.2024.141793
Received 12 May 2023; Received in revised form 26 February 2024; Accepted 13 March 2024

2022). Further, this agenda has become more significant after the recent staging of the COP26 UN Climate Change Conference in Glasgow (Lu et al., 2022), followed by the COP28 in Dubai.

Conceptually, agriculture is a food producing economic activity that defines the current and future food security of the global economies (Rizal and Anna, 2019) whereas “productivity measures the amount produced by a target group (country, industry, sector, farm or almost any target group) given a set of resources and inputs” such as land and labour (FAO, 2017b, p. 10). Despite all the scientific and technological developments in enhancing the harvests, the success of agricultural production has remained highly reliant on climate (Aggarwal et al., 2019) due to: (i) intensifying CO2 on respiration, mainly for *C3* plants (Bocchiola et al., 2019; Magazzino et al., 2023) (ii) varying temperature and fluctuating precipitation (Gwambene et al., 2023), (iii) altering harvests along the 21st century, and so on (Bocchiola et al., 2019; FAO, 2022; Prăvălie et al., 2020; Ahmed et al., 2023). Given the general rule of thumb in the equatorial tropics, every 1 °C increase in the average temperature causes a 10% plunge in the yields of crops (Sova et al., 2019). Likewise, with reference to the baseline condition of “no climate change”, the global climate change causes a 1–5% plunge in harvests per decade (Chowdhury et al., 2022), especially in yields for vital crops such as maize, rice and round potato (Gwambene et al., 2023; Gwimbi and Mundoga, 2010; World Bank, 2013). Further intensification of the climate change is predicted to lessen agricultural productivity by 15.9% globally, 19.7% in developing countries, and a staggering rate of decline of about 15–35% in Africa by the 2080s (Fischer et al., 2005; Pickson and Boateng, 2021). In the rural areas, climate changes, such as rising temperature, salinity intrusion, famines, storms, floods, and lingering and shrinking rainy seasons curtail agricultural and animal productivities, raise herd mortality, and subsequently pose serious threats to food security and nutrition (Chowdhury et al., 2022; Meyfroidt, 2017).

Conceptually, food security refers to the conditions “when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life” (Peng and Berry, 2019, p.1). Due to the continued fall in the staple crop harvests as a consequence of climate change, global food security is facing high risk (Bocchiola et al., 2019; Parry et al., 2004**)**, particularly in tropical and Mediterranean countries (Hendriks et al., 2022) and the regions that lack adaptability (Sova et al., 2019). Estimates suggest that every ninth person worldwide (805 million) encounters food shortages (Chowdhury et al., 2022), and 11.9% (927.6 million) of the world population have encountered ominous food insecurity issues whereas 25.9% of the African population faced the same in 2020, inflating the sum of starving populations by an alarming number of 46 million within a year, 2019–20 (FAO, 2016). At the same time, Asia had 54% (418 million) of the world’s malnourished population (768 million) whereas Africa homed about 37%. Within Africa, the proportion of malnourished population in 2020 ranged from 7.1% (17.4 million) in the North to 31.8% (57.1 million) in Middle Africa (FAO, 2016). While Eastern Africa recorded the largest number of undernourished people in 2020, the rates of increase in the South, the West and the East were 10.1% (6.8 million), 18.7% (75.2 million) and 28.1% (125.1 million), respectively (FAO, 2016; Pickson and Boateng, 2021). Further, predictions by the international bodies highlight a frightening picture. For example, in the year 2017, the IPCC predicted contribution of climate change to a 20% rise in the risk of hunger and malnutrition by 2050 (IPCC, 2017) whereas the assessment report AR5 of the IPCC forecasted likely exposition of an additional 5–200 million people to starvation by 2100 (Bocchiola et al., 2019). The UN Food and Agriculture Organization **(**FAO) projected fall of an additional 122 million people into poverty by 2030, and contraction of GDP of the world’s poorest nations by up to 30%, slowing the likely reduction in inequality amid countries (Diffenbaugh and Burke, 2019).

The contemporary natural calamities in Africa, such as the destructive cyclone Kenneth and Idai, the flooding and the continuing locust epidemics in the East of Africa, the famines in the South and East of Africa, and the Sahel’s desertification, have resulted altogether in severe food insecurity, threatening the livelihoods of millions of people in the region, leading to a persistent mass exodus (Song et al., 2022). However, given that 26.5 million people face serious food insecurity, another 7.2 million risk hunger, and 12.8 million children suffer from severe malnourishment, situations across East Africa are worsening fast (Reid, 2022). Among the East African nations, Ethiopia, Sudan, and South Sudan had been the worst sufferer of the 2020 food crises caused mainly by climate change (e.g., famine), and partly by alterations in the allocation of pests and unresolved regional conflicts (Global Center for Adams et al., 1990). Earlier, in 2015, Ethiopia, Kenya, and Uganda topped among the most impacted countries in East Africa where 10.2 million people suffered food insecurity caused by the El Nino-induced drought (FAO, 2016b; Song et al., 2022). More recently, among the 60 climate-affected vulnerable countries suggested by the World Bank, 38 belonged to Sub-Saharan Africa (63%), and Burundi, Eritrea, Ethiopia, Somalia, Niger, Gabon, and Madagascar were listed in the high-risk category (Olaoye et al., 2022). Altogether, it is evident that “Africa is suffering enormously from the devastating effects of climate change. [in particular] This is serious in the Horn of Africa due to the droughts in East Africa” (President of Ethiopia, as quoted in Global Center for Adams et al., 1990).

It is evident that the severity of the climatic conditions in Africa, such as floods, famines, intensifying temperatures, and unpredictable rainfall, has been documented in various studies over the last two decades. However, most studies have highlighted a mixed picture of the climate effects on agricultural production, and many others have offered inconclusive outline of the reasons behind the persistently widening inequalities in food production (Ogundari and Onyeaghala, 2021; Pickson and Boateng, 2021). In light of the above background, we investigate the interconnectedness among changes in climate, security of food and agriculture using four major seasonal crops of Cash and Food, i.e., barley, wheat, maize, and sorghum (CSA, 2021), in nine agriculturally rich regions in Ethiopia (Degife et al., 2018). We address three specific objectives and hence: (a) investigate the impacts of climatic change on the agricultural production; (b) examine the crop-to-crop differences among the effects of climatic change on agricultural production; and (c) assess the adaptation steps for climatic change and mitigation of effects on security of food and agriculture. Also, given that the mass population in sub-Saharan Africa (SSA) live in rural areas and rely on agriculture for 80% of their livelihoods (Collier and Dercon, 2014; Jayne et al., 2021), we investigate the main challenges that population on the grassroot level are encountering.

The impacts of climate on agriculture and food security in Ethiopia deserve scholarly attention for multiple reasons. First, Ethiopia has been an icon of the liberation of Africa from the colonial occupation of the continent, a founding member of the UN and the African base for numerous international bodies (Abrahamsen et al., 2023). Given their pioneering roles in Africa and East Africa in particular, it is vital for the emerging economies to learn from their experience. Second, Africa’s second most populous country, Ethiopia homes about 115 million inhabitants and thrives as one of the fastest-growing countries in the region, averaging 9.8% a year (World Bank, 2021). On the contrary, Ethiopia features as a common country in all globally recognised lists related to the severity of climatic vulnerability and its impacts on agricultural production and food security. Third, as an engine of the Ethiopian economy, agriculture employs 75–80% of the inhabitants, and contributes 80% to rural incomes, 40% to GDP and 90% to export earnings (Jayne et al., 2021). However, while shortages in water and recurrent droughts impede the production of agricultural products, the major challenges associated with food security in the country are posed by the degradation and vulnerability of environment (Abrahamsen et al., 2023). Fourth, Ethiopia ranks the second for sorghum, the third for maize and wheat, and the fourth for coarse grains in Africa (CSA, 2021). The country also ranks the first for livestock population in the entire African continent (CSA, 2021), contributing 40% to agricultural GDP, about 20% to national GDP, and 20% to export earnings in 2017 (World Bank, 2021). Despite all these achievements including remarkable success in counteracting chronic food insecurity, malnutrition and stunting since the Millennium (FAO, 2022), the country still loses at least 16.5% of its yearly GDP to the long-term impacts of climate extremes (Degife et al., 2018; Deribe et al., 2021), fuelled by persistent regional conflicts, the recent pandemic, and so on (FAO, 2022).

The rest of the article proceeds as follows. Section 2 presents a review of literature. Section 3 describes data and methodology of this study. Section 4 reports empirical results and holds a discussion of the results. Finally, section 6 draws conclusion.

2. Literature review

In the recent decades, climate change has been increasingly becoming more prevalent, frequent, rapid, unpredictable and unusual compared to that of the past (Moges and Bhat, 2021). Due to its growing significance, scholars across the world have conducted numerous theoretical analyses and empirical investigations on the nexus between climate change and agricultural development (Song et al., 2022). Two parallel focus of studies have evolved: (a) the growth and yield of various types of crops, such as maize (Brown and Rosenberg, 1999; Gwimbi and Mundoga, 2010), wheat (Brown and Rosenberg, 1999), rye (Chmielewski and Köhn, 2000), potato and barley (Holden et al., 2003), root and tuberous crops; (b) agricultural output on the country and/or regional levels, such as Australia, Canada, USA and Spain (Hill et al., 2001), Germany (Chmielewski and Köhn, 2000), Greece (Nastis et al., 2012), Italy (Moonen et al., 2002), Romania (Prăvălie et al., 2020), China (Bai et al., 2022; Song et al., 2022; Zhou et al., 2022), India (Aggarwal et al., 2019; Gupta et al., 2014), Bangladesh (Chowdhury et al., 2022), Bhutan (Chhogyel and Kumar, 2020), Nepal (Bocchiola et al., 2019), Kazakhstan (Mizina et al., 1996), Egypt (Yates and Strzepek, 1998), Saudi Arabia (Alkolibi, 2002), Nigeria (Ani et al., 2022), Tanzania (Gwambene et al., 2023), Zimbabwe (Matarira et al., 1996), Africa (Pickson and Boateng, 2021), Europe (Ewert et al., 2005), developing world (Gwambene et al., 2023; Halissou et al., 2021), arid regions (De Pauw et al., 2000), and so on. Given the above backdrops, we review relevant literature in the global and the Ethiopian contexts in section 2.1 and set the background to formulate testable hypotheses of relevance in section 2.2.

2.1. Climate change, agricultural productivity and food security

2.1.1. Global context

In reality, the increase in the levels of population, innovation, living standards, and progress in technology, industry, and infrastructure are resulting in contraction of trees and agricultural land (Evangelista et al., 2013) while the exceeding greenhouse gas (GHG) over the high concentrations levels of earth during the 800,000 last years (IPCC et al., 2014) are inhibiting agricultural productivity (Adom and Amoani, 2021). In North Europe, east regions of North America, South America, North Asia as well as Central Asia, precipitation levels are rising. The Tropics and Subtropics regions suffer from lingering droughts while Sahel, South Africa and Central Asia enjoy the parched lands (Balting et al., 2021). The FAO estimates predicted prolonged suffering of the global food production due to worsening weather shocks as well as continued declines in agricultural yields until 2030, if a “business as usual” attitude persists with regard to the issue of climate change (FAO, 2016). Moreover, IPCC (2017) estimates predicted a 20% higher risk of hunger and malnutrition by 2050. Given the UN projection that the world population will reach about 10.4 billion in 2080 (Song et al., 2022) and the prediction of the fourth assessment report of IPCC (2007) that people who are struck hungry worldwide will represent 200–600 million in 2080, majority of the countries today are prioritising policy to enhance agricultural productivity. However, as the Organisation for Economic Co-operation and Development (OECD) reported, “in the context of the Sustainable Development Goals, and the objectives defined at the UN Food Systems Summit, governments face the challenges of producing more food to feed a growing global population, without depleting land and water resources, and contribute to lowering greenhouse gas (GHG) emissions” (OECD, 2022, p.4).

Contemporary studies have offered a mixed bag of findings with regard to the impacts of climate change on agricultural productivity. For instance, Parry et al. (2004) examined various effects of climate change on agricultural production, crop yields and risk of hunger, and revealed an estimated loss of about 30% in developing countries, particularly in Africa and partly in Asia. Thurlow et al. (2009) investigated a worst-case rainfall scenario in Zambia and suggested an estimated cost of US$ 4.3 billion over a decade, projecting a further rise to $7.1 billion. Lin and Lu (2019) observed a negative nonlinear correlation between rising temperature and the total factor productivity (TFP) of winter wheat. Likewise, Nechifor and Winning (2019) observed a negative effect of the rise in temperature on agriculture, suggesting ways of mitigating the impacts based on technology innovation, guaranteed policy instrument, agro-focused infrastructure and so on. Similarly, Birthal et al. (2021) found a significantly inhibitive effect of climate change, heat in particular, on crop yield in India. In the context of Sri Lanka, Suresh et al. (2021) recorded a negative consequence of climate change on agricultural productivity. On the contrary, Gao (2018) examined the impact of sunshine hours and rainfall on agricultural productivity in western China and suggested a positive nexus between them. More recently, Jabal et al. (2022) reported less sensitivity of the summer crops like rice, maize, and sunflower to the temperature in Iraq, known to be one of the semi-arid regions in the world. Some scholars reported mixed findings from single country studies. For example, Yin et al. (2016) used rise in temperature as a proxy of climate change and assessed its impact on agricultural productivity in various regions of China. The findings suggested that rising temperature hindered the TFP in the eastern and south-western regions whereas the same boosted the TFP in the north-eastern, northern, north-western, and southern regions. Likewise, Yi et al. (2021) reported a significantly positive impact of the yearly average temperature on TFP, and significantly negative effects of yearly rainfall, density of rainfall, and severely high or low temperatures on TFP.

Extant literature emphasises the significant influence of the long-term implications of the fall in the harvests of staple crops on food security and socio-economic stability (Msowoya et al., 2016). In connection with the types of crops, a number of studies have postulated climatic vulnerability as the main driver of the losses in harvests (Ben-Ari et al., 2016), especially precipitation and rising air temperature (Xu et al., 2016). Gupta et al. (2014) analysed the yields of the main grain of food and grain of non-food crops in India and noted evidence of a negative impact of climatic change on rice, sorghum, and millet. Stevanović et al. (2016) revealed that the global economic losses in maize, wheat and barley cultivations created by climate change have already reached an alarming figure of US$5 billion per year. Ramirez-Cabral et al. (2017) anticipated a substantial rise of monetary losses to staple crops (e.g., maize) in the coming decades, if the current pace of changing climate (e.g., heat and dry stress) continues. On the contrary, a group of scholars have indicated some exceptions to the above results. For instance, Li et al. (2011) used variations in temperature and precipitation as proxies of climate changes and examined maize productivity in the US and China. The authors observed no evidence of negative effects of climate on maize yields. On a regional study within China, Li et al. (2014) found mixed evidence of a likely fall in maize yields in the North-eastern region and a rise in the South-western region by 2030. Likewise, on a global level, Liu et al. (2020) assessed the impacts of temperatures at various points of time and observed positive effects of a 1.5 °C rise in temperature on corn yield and opposite effects in connection with a rise over 2 °C.

2.1.2. Ethiopian context

In Ethiopia, “cereal crops dominate crop production and human diet” (Bezabih et al., 2023, p.1) and this is of importance in this study due to its focus on agricultural production and food security. Ethiopia produced 34.2 million tons of crops in 2020/21 (CSA, 2021), using 81% of the 13 million hectare of total cultivable land for cereals, 13% for pulses and the remaining 6% for oil seeds. The total cereal production, comprising maize (31%), wheat (17%), teff (16%), and sorghum (13%), is mostly used for household consumption, and this is unlike pulses, oilseeds and partly fruits, which are used primarily for generating export earnings (CSA, 2021). Maize is a significant crop that addresses Ethiopia’s local needs of foods and exportations. Ethiopia stands as a leader country in exporting Maize. The crop is influenced by climatic variation and demands 21–30 °C as a uniform temperature that 50–100 cm rainfall accompanies it. Wheat is the third most dominant crop after teff and maize in Ethiopia, growing in the temperature ranging 14–18 °C. Oromia, Amhara, South Nation Nationality and People, and Tigray are examples for the main regions with high yield of wheat. It is a rabi crop which necessitates a 50–100 cm rainfall. The growing demand for sorghum worldwide has turned sorghum as a significant income source to the country. It is grown in the sub-tropical and tropical parts of Ethiopia. As per the FAO (2013) estimates, Southern Nations, Nationalities and Peoples Region (SNNPR) and Tigray have the greatest sorghum yield whereas the biggest area for sorghum productivity is inside Oromiya and North Gondar and North Shoa in Amhara. Sorghum cultivates well in between 20 and 40 °C, requiring an adequate rainfall of 1000–1100 mm for a high yield. Barley grows in the sub-tropical and the tropical regions of Ethiopia. It necessitates a mild winter climate and grows best in climates such as dry and cool rather than hot and moist ones. It is produced in Oromia, Amhara, Tigray and southern nation nationality and Regional State.

All crops in Ethiopia, especially barley, are extremely prone to the detrimental impacts of climate change and variability (Moges and Bhat, 2021; Bryan et al., 2009), and this is in consonance with the experience of the most developing countries, Africa in particular (Olaoye et al., 2022). The features of climatic changes are reflective of harsh consequences on agricultural productivity (Yalew et al., 2018), affecting the livelihoods of millions of people and posing challenges to food security in the coming decades (Wendimu, 2021). Similar to the global experience, studies (e.g., Deressa and Hassan, 2009; Robinson et al., 2011; Solomon et al., 2021) have offered mixed findings of climate impacts for various agroecological zones (AEZ). For instance, Deressa and Hassan (2009) highlighted that rising temperature reduces the net revenue per hectare in Ethiopia by US$997.85 and US$1277.28 in winter and summer seasons, respectively. The authors also predicted a decline in crop net revenue (worth 0.5 tons per hectare) by 2050 and 2100. Robinson et al. (2011) used the baseline of “no-climate change” and assessed the implications of climate changes on GDP, income and consumption in Ethiopia. The authors forecasted that by the year 2050, the GDP will be lower by 10 in relation to the baseline. Likewise, Solomon et al. (2021) applied a “no-climate change” baseline and forecasted 5–10% worse performance of the agricultural production in Ethiopia as a result of the climate changes. The authors also predicted 25.4%, 21.8% and 25.2% decreases in the outputs of teff, maize and sorghum, respectively by 2050 compared to the baseline. However, Zenebe et al. (2011) examined the implications of climate change on various AEZs of agriculture and reported marginal impacts of the climate variables (e.g., temperature, rainfall) on the net revenue per hectare for crop, livestock and mixed agriculture in Ethiopia.

It is evident that climate change has produced a mix of negative and positive effects on crop yields in various parts of the world including Ethiopia. However, given that predictions regarding the consequences of climate change on agricultural productivity, especially crop-specific yields, have remained mostly ambiguous (Prăvălie et al., 2020; Zhang et al., 2015), the aim of this study is well-justified and significant in the context of the developing countries.

2.2. Formation of hypotheses

A large majority of the population in Ethiopia are directly reliant on rainfed production systems, which are affected by climate change (Mohammed et al., 2022) which is “characterised by highly erratic rainfall, frequent droughts that often cause famines, and intensive rainfall that often cause floods” (Deressa and Hassan, 2009, p.21). The crop damage associated with climate change (e.g., varying weather patterns) adversely affect yields between 12 and 13% (Rwanda, Uganda) to 36% (Ethiopia), subsequently hampering food security of at least 40% of farmers during the agricultural season (Thomas, 2020). In Ethiopia, the monsoon is therefore a core factor to determine the yield’s quality and quantity. Given this background, we focus on the nexus of the changing climate with agricultural productivity and food security, and formulate corresponding hypotheses in the context of Ethiopia.

Lately, Ethiopia experiences hotter temperatures and different levels of precipitation. The World Bank (2021) predict an increase in the temperature of the subtropical and the tropical part of Ethiopia that can lead to an adverse impact on the crops’ production such as barley, millet, sorghum, wheat, beans, and maize. These crops require high temperature over the sowing period. However, the temperature rising beyond a limit may lead to a distortion of the crop’s intermolecular linkages, hence preventing the required level of maturity. It also reduces the groundwater levels, implying that areas which were historically dry becomes drier. This shortage in water therefore has a negative influence on the cultivation of crops, signifying the dependence of harvests on rainfall until today, and a positive nexus of farm activity in Ethiopia with monsoon. Research has indicated that there is a need for a high rainfall level over the period of growing maize, sorghum and barley. Maize productivity in Ethiopia is mainly associated with rainfall due to the requirement of a large quantity of water supply. For example, production of a single kilogram of maize necessitates higher than 2–3 L of water per day (FAO, 2013). In case of sorghum, an increasing rainfall in the ripening stage can present serious implications for the crop’s growing. It can be leading to an increment in the level of moisture inside the tissue which gives way to the growth of vegetative. Moreover, it can destroy the harvest or lead to a low yield. Other possibility could be the rainfall variations in seasons which might influence the sorghum’s schedule of sow and harvest, destabilising the patterns of productivity and subsequently resulting in low production. Likewise, Barley requires high levels of water in the planting stage, which justifies its visibility in the rainfall dominated regions (FAO, 2013). All these backdrops associated with maize, sorghum and barley imply that the more an arable land comes under the irrigation facility, the greater will be the yields of these crops as well as their protection from the likelihood of droughts. In summary, the size of the irrigated area and the amount of rainfall explain why the states lacking enough rainfall show reliance on irrigation and subsequently have big crop sown area (FAO, 2013).

Considering the above discussion, we formulate the following hypothesis:

> “**The higher the gross area irrigated, the higher productivity will be**”.

“Of all the resources involved in the production process, the most important is workforce” (Smirnova and Postnova, 2020, p. 1). In the emerging market and developing economies (EMDEs), including Sub-Saharan Africa (SSA) and East Asia and Pacific (EAP), agriculture accounts for about 30% of employment whereas for the low-income countries (LICs), the rate is over 60% (Restuccia and Rogerson, 2008; Dieppe and Matsuoka, 2021) Amongst the most populated countries, Ethiopia (66%) have the largest share of agricultural labourers, followed by closely by Tanzania (65%) and other low income and lower-middle income countries from Africa (Ryu, 2023). In terms of both direct and indirect involvements, the proportions of the population in SSA countries and in Ethiopia are 75% and 80% respectively (Moyo, 2016; Workneh et al., 2021) The burgeoning population and the mounting pressure on limited arable land cause a serious food and cash crops shortage in Ethiopia. Maize is the leading commercial crop that bears the major load of addressing the growing shortage of food in the country. Nonetheless, the Ethiopian Government estimates show a 20%–43% decline in the maize productivity during 2014–2021 (CSA, 2021). This fall is caused by climate change and the shift of farmers and labourers from producing maize to easier to manage crops. For example, although workers in agriculture represent a main key for the maize production, some of the laborers in agriculture who cultivate the maize switched to producing soybean that now brings 18% to the country's total productivity of oil crop (Siamabele and Moral, 2021). Estimates on the sectoral level reveal a shift of labour from low-to high-productivity sectors, accounting for about 40% of workers' productivity growth in the EMDE economies (Dieppe and Matsuoka, 2021). Nonetheless, given that about 23% of the SSA's GDP come directly from agriculture, and smallholder farmers consist of more than 60% of the SSA population, compared to the small corresponding numbers of the US (3%) and Japan (4%) (Ryu, 2023), the contribution of the agricultural workers in the sector's productivity is of paramount important.

In light of the above discussion, we propose the following hypothesis for empirical testing: "**The higher the agricultural workers, the higher productivity will be**".

The limit in land availability compared to the increasing need of grazing and cultivation activities has a direct influence on the forest area and use of fertilisers. Given that agro-based economies' goal of increasing production of crops needs acquisition of more cultivable lands, agricultural activity has emerged to be the main reason to reduce the area of forest, as revealed by the FAO report (2016) on the state of the world's forests. Unlike many of the developed countries that have managed to recover from their losses in forest and started expanding the forest area, the deforestation and destruction of forests are occurring for countries with a cheap scale of income, mainly in tropical areas (Kirilenko and Sedjo (2007).While attempting to multiply the yields of maize, Ethiopia might reproduce a similar experience of deforestation that Brazil had more than a decade ago (USITC, 2011). Like maize, Barley is considered as a basic crop of people living in the sub-tropical and the tropical national regions of Ethiopia. The boom of population that increments the crop's demand has required a larger area of cultivation that can uniquely be realized through the compromise of the cover of forest. On the contrary, area of forest can indirectly affect the production of crops through afforestation. It implies the reduced shocks that crops will have from the decelerating pace of global warming and recurring climate events as a result of increasing afforestation activities.

Considering the above observations, we propose the following hypothesis for testing: "**The higher the forest area, the higher productivity of the crop will be**".

Fertilizers have played a crucial role in bolstering crop yields and hence enabled making reduced use of land for agricultural cultivations and, more importantly, feeding at least half of the alive population across the globe today (Ritchie et al., 2022). Likewise, the use of fertilizer has played an important role in the agricultural revolution in Ethiopia that witnessed some positive outcomes in the yield of crops. During 2007–2012, use of fertilizer increased by 60% and consequently Ethiopia's agricultural production enhanced by about 30–40% from 2004 to 2014 (Rashid et al., 2013). While Amhara, Oromia, SNNP and Tigray regions necessitate greater fertilizer consumption due to the type of soil and cultivated large area, other regions, such as Afar, Somali, Gambella, and Harari, require a low consumption. However, although the fertilizers' supply of the primary nutrients in the forms of nitrogen, phosphorus and potassium is enhancing the soil efficiency (UNEP, 2022), estimates suggest the lowest fertilizer nutrient use in SSA in the world, i.e., less than 20 kg ha^{-1} against the global average of 135 kg ha^{-1} due to high cost of purchase, inadequate production and distribution infrastructure, and poor timely availability (Intelligence, 2016). The poverty statues of economy for a large farmers section in Ethiopia is making it hard for the small and marginal farmers the utilization of varieties that are highly yielding fertilizers. This worsened the already persistent poor crop yields and deepened food insecurity in the region. For instance, during the 2022 harvesting year, production of cereals plummeted by 16% (year-on-year) in East Africa and the size of the food insecure population enhanced by nearly 6–7 million people by the end of 2022 (WFP, 2022). In addition to this, many countries overapply fertilizers and contribute to environmental pollution in the form of running-off of nutrients into water systems and ecosystems (Ritchie et al., 2022). Against all the odds, studies (e.g., Njoroge et al., 2023) pinpoint the importance of increasing the usage of fertiliser in elevating crop productivity and hence accomplishing food security in Africa at large.

Considering the above information, we propose to formulate the following hypothesis: "**The higher the fertilizer consumption is, the higher productivity will be**".

A country's efficient food security system relies largely on agricultural mechanization and, without this, accomplishing SDGs become challenging for SSA economies, Ethiopia in particular (Workneh et al., 2021; Smirnova and Postnova, 2020). Agricultural productivity in SSA has however remained low due to low levels of mechanization (Dayou et al., 2021). According to their order, wheat, maize, teff and sorghum are relatively more mechanized crops in Ethiopia (Deribe et al., 2021). As a strategically important direction for mechanization of the industry, "farm tractors play a very important role in agriculture, as they are the power source for various attached implements and agricultural machinery" (Janulevičius et al., 2019, p.80). In Ethiopia, the landholdings of small and marginal farmers (Dayou et al., 2021) have narrowed the scope of employing tractors, which are highly expensive and hence less cost efficient for tiny arable lands. Following Rwanda, Ethiopia ranks the second from the bottom among nine SSA economies by having only 4 tractors per 100km2 of lands, which is far below the sub-regional average, i.e., 13 per 100km2 (Gebiso et al., 2023). Further, due to the lack of trained workers to address the challenge of tillage development in African agriculture, the tractors may not be employed in the right parts of agriculture and in the right kind of soil (FAO, 2017), leading to degradation of soil and subsequently hamper the crop production. On the contrary, on the policy level, the Ethiopian Government formulated an agricultural mechanization strategy to enhance food security and achieve a middle-income status of Ethiopia by 2025 using a sustainable approach, e.g., promoting tractors to lessen post-harvest losses from 20% to 5% and magnifying its mechanical power index to 3.35 hp/ha (Workneh et al., 2021). However, despite the global recognition of the significance of farm mechanization and also compared to the volume of studies conducted on agriculture related issues in general, "studies on farm mechanization are very limited and there are no quantified research outputs on level of farm mechanization, socioeconomic, demographic and other variables that affect the uptake of farm mechanization in Ethiopia" (Gebiso et al., 2023, p.2).

Considering the above observations, we propose the following hypothesis for testing: "**The higher the number of tractors, the higher productivity of the crop will be**".

In poor agrarian economies of Africa, workers in general have appeared to be more productive in the labour-intensive farms which generally not large in size, compared to those using advanced machines that contribute much to the respective country's income (Collier and Dercon, 2014; Lowder et al., 2016). Due to the abundance of relatively unproductive resources (e.g., land and labour), the small farms have witnessed broad based rises in the productivity of staple food workers, contributing to the enhancement of the livelihoods of grass-root people (Dorward, 2013). Likewise, Ethiopia uses more workers in agriculture in order to increase the productivity of crops, reflecting the tradition of the poverty-stricken states in Africa where agricultural sector relied on applying labour-intensive methods of cultivating crops, implying a positive nexus between the size of the labour force and the volume of crops production, wheat in particular. However, there are rising concerns that decline in the availability of labour in both short- and long-term periods may endanger agricultural production, resulting in national food security (Balwinder-Singh et al., 2020).

Considering the above scenario of the agro-based workers, we propose to formulate the following hypothesis: "**The higher the agricultural workers, the higher productivity will be**".

In recent years, the world has witnessed swelling average food prices, acute food price shocks (in 2008 and 2010/2011) and growing concerns about the effects of food price shocks, inflated food prices and food price volatility on food insecure people under poverty line (Dorward, 2013). In the developing world, Sub-Saharan Africa (SSA) in particular, the close links of food prices with the production, and associated price fluctuation affect food security for farmers, who are both producers and consumers of their harvests (Amolegbe et al., 2021). Given this background, farmers using conventional and less intensive methods of cultivation end up facing volatile food prices (El Benni and Finger, 2014). However, net sellers make economic gains when food prices go up in local markets, provided production costs remain unchanged. On the contrary, as suggested by Wossen et al. (2018) based on their study on Ghana and Ethiopia, producers in developing countries are primarily net buyers of foodstuffs. Since they eventually spend more than their earning from the sale of their harvest(s), they refrain from cultivating more for the market (Assouto et al., 2020).

Considering the above discussion, we propose to develop the following hypothesis: "**The higher the farm harvest price, the higher productivity of the crop will be**".

The hypotheses are summarised in Table 1 below.

3. Methodology

3.1. Data and variables

In this study, we examine four major crops of Food and Cash in Ethiopia, i.e., barley, maize, wheat, sorghum, over the period 2011–2020. Nine states that are intensive in agriculture activities and have variety of climate conditions in the tropical and subtropical zones in Ethiopia are taken into accounts in this study. Afar, Somali, Gambella, and Harari belongs to the tropical zones while Oromia, Amhara, Tigray and Southern Nations, Nationalities and Peoples Region (SNNPR) represent the subtropical zones. We do not include all Ethiopian states in the modelling for two main reasons: First, due to the existence of a massive divergence in every state's temperature, the findings are likely to be misleading and not robust. Second, lack of similarity of intensity of agricultural productivity and activity among states.

The relation among climatic change and agriculture production over the period 2011–2020 is analysed through empirical modelling based on panel data estimation. The agriculture production measured by kg in hectare is selected as the explained variable, while average minimum temperature (MIN) and average maximum temperature (MAX), irrigated gross area (GA), total fertilizer consumption (FC), workers in agriculture (AW), number of tractors (TR), total area of forest (FA), harvest price in farm (HP), annual rainfall on average are used as the independent variables. These inputs are then separated to exogenous and endogenous inputs. While the endogenous variables are represented by GA, FC, AW and TR, the exogenous inputs which influence the dependent variable are FA and HP. Table 2 presents a brief description of variables.

We obtain the data that can be splatted in two parts: variables based on agriculture and meteorology. The mentioned data representing the considered variables of agriculture in the study is collected using a number of sources, i.e., data of crop wise agriculture production by kilogram per hectare (TP), irrigated area's crop wise gross by thousand hectares (GA), total area of forest by thousand hectares (FA), number of total tractors utilized in the land (TR), fertilizers' total consumption by kilogram per hectare (FC) and number of workers in agriculture (AW). The data on hectare yield of the four crops is obtained based on the annual agricultural sample surveys of the Central Statistics Agency (CSA) of Ethiopia. Data on GA, FA, FC, and TR is also extracted through the annual agricultural sample surveys of the CSA of Ethiopia. GA, FA and FC representing the explained variable in this study (i.e., agriculture production) are computed in thousand hectares and kilogram per hectare, respectively. The so-called data for Meteorology as wise annual rainfall in state and wise maximum and minimum temperatures in state are the variables of climate. Annual data of wise rainfall in state and wise minimum and maximum annual temperatures in state for the years period 2011–2020 has been obtained from the database of the National Metrological Agency (NMA) of Ethiopia.

3.2. Process for selection of consistent empirical model

Panel Data Estimation: The present study is panel data estimation and yields of various cash crops are included as output for nine states of Ethiopia during, 2011–2020. These all states have high disparities in climatic parameters as well as high regional inequalities in socio-economic characteristics. Thus, there is needed to estimate the tests like panel unit root and state-level fixed effects. The unit root test talks about whether individual time series data is stationary or not and the fixed effect test is quite useful to capture the unobserved heterogeneity across states. We included year-specific effects to control for annual difference in yield for all the states (Cabas et al., 2010; Gupta et al., 2014).

Panel Unit Root Test: Unit root test helps to identify the stationary of a time series data (McCarl et al., 2008; Kim and Pang, 2009; Poudel et al., 2014). If the individual time series data is not stationary, it will lead to spurious regression and the property of ordinary least square estimation will not be satisfied (Poudel et al., 2014). Inferences of empirical findings may be misinterpreted (Kim and Pang, 2009). We tested the null hypothesis that all panel contain unit roots for all crops. Im-Pesaran-Shin test is rejected the null hypothesis at 1% significant level. Critical values are also found less than the values of t-bar, t-tilde-bar and Z-t- tilde -bar. Hence, we can conclude that all individual time series data sets are stationary for entire crops in proposed models. The Ramsay RESET test is used to identify the appropriate functional form of empirical model (Singh and Jyoti, 2019; Singh and Ashraf, 2020; Singh and Singh, 2020). Statistical results of this test are found

Table 1
List of hypotheses.

Hypothesis	Description
1	The higher the fertilizer consumption is, the higher productivity will be.
2	The higher the gross area irrigated, the higher productivity will be.
3	The higher the agricultural workers, the higher productivity will be.
4	The higher the number of tractors, the higher productivity of the crop will be.
5	The higher the forest area, the higher productivity of the crop will be.
6	The higher the farm harvest price, the higher productivity of the crop will be.

Source: Authors' own development based on literature review

Table 2
The variables at a glance.

Variables	Description
TP	The total productivity for each crop
FC	The total fertilizer consumption
TR	The total number of tractors
FA	The total forest area
GA	The irrigated gross area
AW	The number of total workers in agriculture
HP	The price of harvest in farm in the crops studied
RF	The annual rainfall on average
MAX	Annual average maximum temperatures
MIN	Annual average minimum temperatures

Source: Authors' own development based on literature review statistically significant, and thus, it proposed that log-linear functional form of empirical model is correctly specified (See Table 3).

Fixed vs random effect: We apply Breusch-Pagan Lagrange multiplier (LM) test to check the suitability of ordinary least square (OLS) versus random effect (Cabas et al., 2010, Kumar et al., 2014; Singh et al., 2017). We tested null hypothesis that there is no significant panel effect on yield across state. In this test we are failed to reject the null hypothesis because the estimated Chi2 values are found statistically in-significant. It means that there is no significant variation among the states and random effects model can be considered for mean yield function for all the crops. Further, Hausman specification test is applied to check the appropriateness of fixed versus random effect model (Cabas et al., 2010; Singh and Jyoti, 2019; Singh and Ashraf, 2020). Here null hypothesis is that the preferred model is random effects, and the unique error (ui) terms are not correlated with regressors. But the estimated Chi^2 values are found statistically in-significant at 1% significance level for all the crops for mean yield function. It means that unique error terms are un-correlated with independent variables and can be concluded that fixed effect model may be considered to estimate the regression coefficients (Table 3).

Cross-sectional dependence or contemporaneous correlation: The cross-sectional dependency across entities means that residuals are correlated across states, and it would lead to bias in estimation. Pesaran test is used to check the cross-sectional dependency (Singh et al., 2017; 2019). The null hypothesis is that residuals are not correlated across states. The authors are failed to reject the null hypothesis because estimated values under Pesaran tests are statistically significant that imply the presence of cross-sectional dependency across states for yield for Maize, Sorghum, Barley, and Wheat (Table 3).

Serial correlation and autocorrelation: Serial correlation often arises in a panel when there is a long time series (over 20–30 years). If the serial correlation exists, the standard errors of the coefficients will be smaller than they actually and higher R-squared value. Wooldridge test is used to check the presence of serial correlation in panel data (Poudel et al., 2014; Kumar et al., 2014). We failed to reject the null hypothesis of relationship between time and yield of Maize, Sorghum, and Wheat crops (Table 3). It means that yields for these crops are significantly correlated with across year.

Heteroskedasticity: Ordinary least square (OLS) estimation assumes that there is constant variance with zero mean and there is homoskedasticity in panel data. Non-constant variance might be caused for heteroskedasticity and useless in interpretation of empirical findings. For group-wise heteroskedasticity Modified Wald test is used (Gupta et al., 2014; Singh et al., 2017; 2019). Here null hypothesis is that there is presence of homoskedasticity (constant variance) in fixed regression model. In this case we failed to accept the null hypothesis because estimated Chi^2 values are found statistically significant at 1% significance level (Table 3). Estimates imply the presence of heteroskedasticity in the panel data sets of yield for all crops.

Final Estimation: We applied several econometric models; however, the selection of the model for interpretation is purely based on model fits and statistical hypothesis testing. First of all, we considered a random effect model for all crops by assuming that the variation across states is random and uncorrelated with mean yield function. Fixed effect model considers capturing the unobserved heterogeneity among the states and to control annual difference in output. These two models can be estimate through Just & Pope production function framework and this suggest that maximum likelihood estimation (MLE) will be a best fit compared to feasible generalized least square estimation (FGLS) (McCarl et al., 2008; Kim and Pang, 2009) However, our panel data set has a problem of heteroskedasticity, serial correlation, and autocorrelation due to these reasons we applied Prais Winsten models with panels corrected standard errors (PCSEs) and feasible generalize least square estimation. As complied state-wise panel data of this study have the cross-sectional dependency, group-wise heteroskedasticity and autocorrelation. So, ordinary square estimation, random effect model and fixed effect models are ineffective to produce the consistent regression coefficient of explanatory variables in the proposed model. For this, previous studies have claimed that Prais Winsten models with panels corrected standard errors estimation (PCSEs) model is highly effective to produce better results in presence of aforesaid statistical problems (Poudel et al., 2014; Kumar et al., 2015; Singh et al., 2017).

3.3. Econometric models

The econometric model developed to estimate the panel data is constructed as follows:

$$\mathrm{Y_{sn}} = \beta_1\, \mathrm{X_{sn}} + \beta_2\, \mathrm{L_{sn}} + \beta_3\, \mathrm{T_{sn}} + \beta_4\, \mathrm{W_{sn}} + \mu_{\mathrm{n}} + \nu_{\mathrm{sn}} \tag{1}$$

where,

$$E[v_{sn}|X_{sn}, L_{sn}, T_{sn} W_{sn}] = 0 \tag{2}$$

The independent variables in these equations have parameters which are calculated employing regressions. Whereas, if the independent variable is not observed, a variable which is extern Z_{s} and links the endogenous variable, i.e., X_{sn} will be added. However, this is not correlated with all the exogenous variables (L_{sn}, T_{sn}, W_{sn}). *vsn* is the idiosyncratic error term.

$$\mathrm{Corr}\ (Z_{sn}, v_{sn}) = 0 \tag{3}$$

$$\mathrm{Corr}\ (Z_{sn}, X_{sn}) = 0 \tag{4}$$

By employing panel data, we are able to control the sources that are not proxied or will not be seen and not represent sources of heterogeneity which change among persons. They however have no difference based on time. It is possible the control of variables that are omitted too. The panel modelling runs three essential regressions: the random effects modelling, the fixed effects modelling and the ordinary least squares (OLS) modelling. There is existence of random effects modelling, when there is existence of heterogeneity during the years and with the cases. The fixed effects modelling is present when there is no time variation however there is cases variability. The modelling of OLS is not considering the time period as a factor in the modelling. We run the estimation analysis in the aim to find the better fit for our modelling. The linear regression based on panel-corrected standard errors is applied in the modelling to delete the impact of multicollinearity and heteroskedasticity. In order to compute our parameter values, the linear

Table 3
Hypothesis testing for selection of proper empirical model.

Applied Test	Maize	Sorghum	Barley	Wheat
Ramsay RESET test using powers of the fitted values of yield	100.878***	106.469***	112.370***	118.598***
Breusch-Pagan Lagrange multiplier (LM) test for random effects [*Chibar*^{2} (01)]	0.000	0.000	0.000	0.000
Hausman test for fixed or random effects [*Chi*^{2} (0)]	0.000	0.000	0.000	0.000
Pesaran's test for cross-sectional dependence	46.279***	15.050***	17.636***	14.712***
Wooldridge test for serial correlation and autocorrelation [*F*(1, 29)]	31.039***	4.037**	2.827	2.902**
Modified Wald test for heteroskedasticity [*Chi*^{2} (30)]	33.013***	125.585***	600.625***	259.963***

Note: *, **, *** denotes the statistical significance at 10%, 5%, 1% levels respectively.
Source: Authors' own calculations.

estimation based on panel-corrected standard errors is employed in modelling time series with sectional cross data of OLS. This modelling supposes the heteroskedasticity and correlations of the errors. Following the literature, the panel estimation in econometric micro data is always over regressed because it demonstrates all types of correlations, i.e., temporal and cross sectional. Such dependence results in biased findings. In order to remove the biases and to obtain results that are true and valid, we include the linear estimation in addition to panel-corrected standard errors to have protection from possible correlated residuals.

Based on previous research, the relation among climate change and agriculture productivity is regressed applying two methodologies, i.e., the productivity function methodology and the Ricardian methodology. Following Callaway et al. (1982), Decker et al. (1986), Adams et al. (1990), Rind et al. (1990), and Rosenzweig and Parry (1994), the approach of productivity function employs the function of productivity and the accommodation of various inputs of environment to assess the effect of the inputs on the productivity. The main disadvantage of the productivity function methodology is the fact that it fails to consider the substitutions of farmers that they make in the aim to be faced to the unpredicted shocks of climate. However, the approach of Ricardian contains farmland' value or rent in net for which we examine the effect of climate (Mendelsohn et al., 1994). This method considers both the influence of climatic change on crops production and the farmers' substitutions that is resorting like an adaptative strategy against the climate change or variation. On the other hand, while the approach of productivity function is employed to regress the impact of change in climate over a specific crop, a crops' group or a specific ecosystem over the long and short run, the approach of Ricardian is used to regress the effect on the entire sector of agriculture or a specific branch (De Salvo et al., 2013, 2013a). We will first indicate by this regression analysis the influence of climatic change on every crop, i.e., food and cash, and then on all crops production with use of the approach of productivity function.

The Cobb-Douglas production function is a widely used function in econometrics and we choose to employ it in this research, instead of linear models or quadratic linear models. The Cobb-Douglas production function is considered important in literature for multiple reasons (Muth, 1989; Hossain et al., 2012; Kumar, 2014; Kumar et al., 2015; Gupta, 2016; Mugagga et al., 2020). Firstly, it is a generalized form that can be used to study the production behaviour, profit maximization, and cost structure of any industry. Secondly, it possesses advantages such as the ability to handle multiple inputs, even in the face of imperfections in the market, without introducing distortions. Thirdly, it can handle various econometric estimation problems, such as serial correlation, heteroscedasticity, and multicollinearity, making it a versatile tool for analysis. Additionally, the function facilitates computations and has properties of explicit representability, uniformity, parsimony, and flexibility. It can also help in understanding factor substitution and returns to scale in production functions, incorporating technological change and process innovation, and hence representing aggregate technology effectively. Overall, the Cobb-Douglas theory is widely used in agricultural economics research and its underlying assumptions are of general interest (Sharif et al., 2013; Uddin et al., 2021, 2024). Given its ability to help answer the question of right input combination to obtain maximum output, the application of the Cobb-Douglas production model in the developing country context, in particular, is considered useful (Uddin and Sharif, 2017; Sharif et al., 2022). Furthermore, as African economies are similar in terms of their agroeconomic features, we rely on the explanation provided by the work of Amuka et al. (2018) in which the authors successfully tested the fitness of Cobb-Douglass Production Function in the context of Nigeria. It light of these backdrops, we consider the cobb-Douglas production model as a good fit for our study on Ethiopia, a public sector-driven and agriculture-based economy, displaying constant returns to scale production.

The productivity function as Cobb Douglas is included in the modelling to examine the impact of climatic change on agriculture production. The associated equation is as follows:

$$TP_{sn} = f\{FC_{sn}, GA_{sn}, AW_{sn}, TR_{sn}, FA_{sn}, HP_{sn}\} \tag{5}$$

Where, *TP* denotes the total productivity for each crop, *FC* denotes the total fertilizer consumption, *GA* denotes the irrigated gross area, *AW* refers to the number of total workers in agriculture, *TR* is the number of total tractors on use for land, *FA* is the share of forest area's crop wise, and *HP* is the price of harvest in farm in the crops studied. Moreover, *s* stands for the states' number with regard to each crop and *n* stands for the period of time into consideration.

The climate factors are considered as a factor of input in crop's growth based on productivity modelling as Cobb Douglas. Hence, the equation can be denoted as:

$$TP_{sn} = f\{FC_{sn}, GA_{sn}, AW_{sn}, TR_{sn}, FA_{sn}, HP_{sn}, RF_{sn}, MAX_{sn}, MIN_{sn}\} \tag{6}$$

Where, *MAX* and *MIN* are the minimum and maximum of temperatures on average per year, respectively, and *RF* is the rainfall on average per year. We define the Cobb Douglas Production function by the following equation:

$$\begin{aligned} ln(TP)_{sn} = {} & \beta_0 + \beta_1 ln(FC)_{sn} + \beta_2 ln(GA)_{sn} + \beta_3 ln(AW)_{sn} + \beta_4 ln(TR)_{sn} + \beta_5 ln(FA)_{sn} \\ & + \beta_6 ln(HP)_{sn} + \beta_7 ln(RF)_{sn} + \beta_8 ln(MAX)_{sn} + \beta_9 ln(MIN)_{sn} + Year\,Dummies + \mu s \end{aligned} \tag{7}$$

Where, β_0 denotes the constant of regression and $\beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6, \beta_7, \beta_8, \beta_9$ are the estimated parameters of the corresponding variables. Year Dummies is the time or year-specific effects and μs is the intercept term.

4. Empirical results

4.1. Descriptive statistics

In the period of study (2011–2020), the selected cereal crops produced were measured in millions of metric tons. The average crops production for the study period is 25.342 million metric tons. On average, a total of nearly 37.271 million hectares of arable land and a total of about 17.397 million hectares of forest area were found in the country. There has been an increasing trend in crop production and arable land starting from 2012 (Fig. 1). On average, 29.425 kg per hectare of arable land fertilizer was consumed during the study period. There has been an increasing trend in the total amount of Rainfall every year (Fig. 1). The result also shows increment of temperature over time in the country.

The increase in agricultural production may ameliorate the availability of food and thus is a significant step for achieving food security sustainability. The agricultural activities are mostly influenced through climate and weather. Therefore, in order to guarantee the availability of food, it is important to investigate the climatic change's effect for agricultural productivity. To study such impact, we have employed the linearity method of estimation based on panel corrected standard errors. The data's descriptive statistics is reported into three Tables, 4–6.

We note that contrary to the data on classic panel modelling, our size of panel is too small. The research takes into accounts nine states of Ethiopia ($n = 9$) during a 10-year period ($s = 10$) that considers 90 observations in total. We employed a data that is small due mostly to the difficulties to obtain the dataset of various states of agriculture. The big challenge was to get into the data per year for minimum and maximum temperatures of state-wise as there is extreme variation in the conditions of climate for each district in every state. If we deal with datasets where there is existence of heterogeneity, the panel data estimation will be a useful methodology as it also allows analysing the fixed effects based on longitudinal dataset. We tried to explore the impact of different keys on crops of cash and food through the panels corrected standard errors (PCSEs) methodology, i.e., linear estimation based on PCSEs.

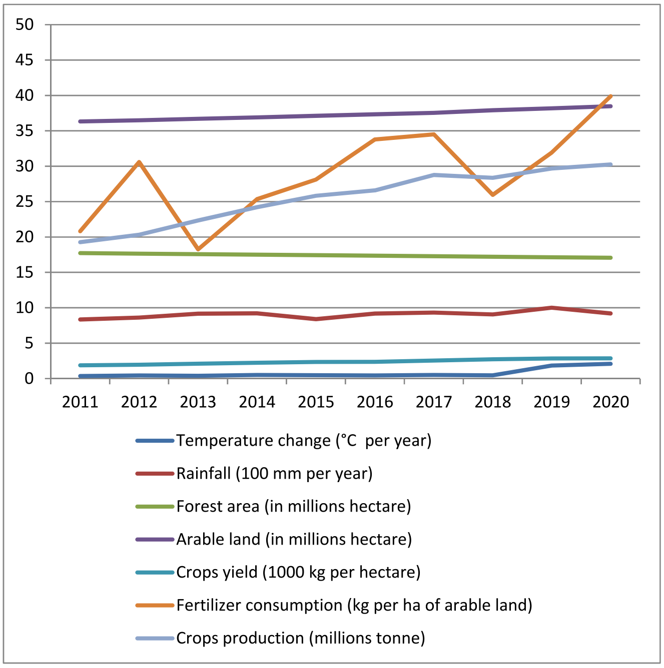

Fig. 1. The trend of indicators for climate change and changes in agricultural production in Ethiopia (2011–2020).

4.2. Findings of research

We provide now the findings of our investigation indicating the effect of variables from meteorology on each crop's production. At first, we choose the sorghum as a first crop. The growing demand for sorghum worldwide has turned sorghum as a significant income source to the country. It is growing on the parts that are sub-tropical and tropical in Ethiopia. Afar, Somali, Gambella, Harari, Oromia, Amhara, Tigray and Southern Nations, Nationalities and Peoples Region (SNNPR) have the best perfect climatic conditions to sugarcane production. In accordance with the Food and Agriculture Organization of the United Nations (FAO, 2013), Tigray and SNNPR have the greatest sorghum yield whereas the biggest area under for sorghum productivity is inside Oromiya and North Gondar and North Shoa in Amhara. The productivity of Sorghum is delicate to climatic variations and cultivates well from 20 to 40 °C. Moreover, in order to get a high yield of sorghum, an adequate rainfall of 1000–1100 mm is necessary. Table 7 (column 3) reports the results of regression for the effect of climatic change and other productivity keys on sorghum production.

The normal evidence is that workers in agriculture, price of harvest, area of forest, and consumption of fertilizer, and maximum temperature present a positive effect on the sorghum production. However, rainfall, minimum temperature, tractors and irrigated gross area present a negative impact on it. The R square value of 0.9747 indicates the existence of 97.47% change in the modelling. Any increase in the tractors usage would be resulting in a negative impact on the yield of sugarcane. By increasing of unit 1 in the machinery tractor, we expect this to result in a decrease of 0.0368 unit in the yield of sorghum ($p < 0.1$). Any raise

Table 4
Summary statistics for the indicators of climate change and agricultural production in Ethiopia.

Variable	Mean	Std.Dev.	Min	Max	Unit of measurement
Temperature	29.70430	59.41150	20.80705	36.17058	Degree °C
Rainfall	903.2483	47.24631	834.6700	1001.380	mm per year
Forest area	17.39700	0.263205	16.99550	17.79850	Million hectares
Arable land	37.27187	0.906278	35.68300	38.59500	Million hectares
Fertilizer consumption	29.42559	7.436521	18.25916	42.07268	kg per hectare of arable land
Crops yield	2.365967	0.387333	1.767300	2.861300	1000 kg per hectare
Crops production	25.34242	4.359140	18.38002	30.24875	Million tonnes

Note: This table presents descriptive statistics for the indicators of climate change and changes in agricultural production in Ethiopia (authors' own calculation).

Table 5
Descriptive statistics for common factors series that influence the productivity.

Variable		Mean	Std. Dev.	Min	Max	Observations
RF	Overall	1332.693	530.7321	766.7	2271.8	N = 91
	Between		502.8241	928.532	2033.5	n = 9
	Within		309.7265	832.5723	1768.101	T-bar = 11.1508
FA	Overall	3241.735	1962.714	1338.728	6675.237	N = 91
	Between		2065.462	1338.971	6371.423	n = 9
	Within		425.6836	657.4384	3545.548	T-bar = 11.1508
FC	Overall	263.5102	58.01008	85.41	401.23	N = 91
	Between		51.1464	212.953	2443.969	n = 9
	Within		39.20823	97.06317	331.6362	T-bar = 11.1508
TR	Overall	33976.90	22879.18	4256	110955	N = 91
	Between		19948.43	10513.187	68917.4	n = 9
	Within		13765.99	7382.743	68919.73	T-bar = 11.1508
AW	Overall	885942	373848.0	435439	1832450	N = 91
	Between		359877.6	509861.5	1600993	n = 9
	Within		169403.5	456367.2	1290255	T-bar = 11.1508
MAX	Overall	29.87912	5.333776	18.3	35.1	N = 89
	Between		5.410992	21.8672	33.103	n = 9
	Within		2.268750	25.67849	33.27624	T-bar = 10.9046
MIN	Overall	16.35807	5.362549	7.17	23.80	N = 89
	Between		5.568281	9.248	12.428	n = 9
	Within		0.9891669	14.13744	19.69131	T-bar = 10.9046

Note: *RF* is annual average rainfall, *FA* is forest area 's share of crop wise, *FC* is total fertilizer consumption, *TR* is number of total tractors in use, *AW* is number of total agricultural workers, *MAX* and Min represent annual average maximum and minimum temperatures, respectively.
Source: Authors' own calculations.

Table 6
Descriptive statistics for specific factors-crops series.

Variable		Mean	Std. Dev.	Min	Max	Observations
GA-wheat	Overall	1835.492	3572.105	0	10263.88	N = 91
	Between		3729.314	0.0427	10034.67	n = 9
	Within		225.4407	1490.450	2071.675	T-bar = 11.1508
GA-maize	Overall	377.944	595.5095	0.1307	1935.97	N = 91
	Between		624.1015	1.81807	1553.092	n = 9
	Within		95.77358	−184.0414	661.8299	T-bar = 11.1508
GA-sorghum	Overall	724.4481	749.9103	8.367940	2222.12	N = 91
	Between		789.7212	12.76997	2186.160	n = 9
	Within		105.8591	421.7818	971.9787	T-bar = 11.1508
GA-barley	Overall	3212.67	2647.033	493.1	6290.60	N = 90
	Between		2744.100	519.419	5967.998	n = 9
	Within		359.9970	1093.9723	4211.910	T = 11
TP-maize	Overall	510.0013	256.7530	50	816	N = 82
	Between		235.7375	292.2646	726.6	n = 9
	Within		106.7972	327.7282	767.4213	T = 9.90465
TP-sorghum	Overall	95829.69	16245.54	65226	130607	N = 91
	Between		16236.14	62635	120483.1	n = 9
	Within		8003.78	63110.58	122815.6	T-bar = 11.1508
TP-barley	Overall	3610.41	684.2648	2503	5135	N = 91
	Between		663.3568	2824.5	4267.9	n = 9
	Within		362.5031	3129.97	4792.70	T-bar = 11.1508
TP-Wheat	Overall	3055.757	1025.151	733	4435	N = 81
	Between		1074.339	1035.5	4049.3	n = 8
	Within		340.2474	2556.432	3530.913	T-bar = 11.1759
HP-barley	Overall	1072.162	453.1657	611	2684	N = 91
	Between		79.69552	979.3	2066.1	n = 9
	Within		551.5911	588.1407	2590.012	T-bar = 11.1508
HP-Wheat	Overall	2243.340	441.465	770	3161	N = 71
	Between		371.1634	3176.8	3627.0	n = 7
	Within		411.2657	777.7344	2915.756	T-bar = 11.3
HP-maize	Overall	3930.140	2021.855	2511	6249	N = 70
	Between		404.1738	3421.0	4153.6	n = 7
	Within		1084.205	2320.044	6024.220	T-bar = 11.3
HP-sorghum	Overall	455.4294	551.6951	100	3049	N = 41
	Between		350.7025	283.3	784.18	n = 5
	Within		507.9533	−228.2224	2720.89	T-bar = 8

Note: *GA* is gross area irrigated, *TP* is total productivity for each crop, and *HP* is price of harvest in farm of studied crop, respectively.
Source: Authors' own calculations.

in the price of cotton harvest in farm would lead to a positive impact on the yield of sorghum. By an increasing of 1% in the price of harvest in farm, we expect this to result in an increasing of 0.0161% in the yield ($p < 0.1$). The temperature in maximum presents a positive effect and the temperature in minimum presents a negative impact on the sorghum yield. However, they both not having significance. It is valuable to observe that the influence of rainfall on the sorghum production is negative. The rainfall increasing 1% diminishes in significant way by 0.1472% the yield. Research has indicated that there is a need for a high rainfall level over the period of sorghum growing; however, an increasing rainfall during ripening can present serious implications for the crop's growth. It can lead to an increment in the level of moisture inside the tissue which gives way to the growth of vegetative. Moreover, it can destroy the harvest or lead to a low yield. Other possibility could be the rainfall variations in seasons which might influence the sorghum's schedule of sow and harvest, which disturb the patterns of productivity resulting in low production. The raise in area of forest impacts the production in a positive way. The area of forest increasing 1% is leading to an increasing of 0.8725% of the sorghum yield ($p < 0.01$). This finding corroborates hypothesis 5. Area of forest shows an indirect effect on the crops production. When the forests areas are experiencing an afforestation and an increase, the pace of global warming will be decelerated and the chances of extremely successive climate events which protect the crops of the suddenly climatic shocks will be reduced (see Table 5).

We considered the maize as a second crop – amounting an annual average global production of 1127 million t (2016–18, OECD, 2022). "The queen of cereal crops" (Mohammed et al., 2022), maize addresses the increasing food needs and supports maintaining Ethiopia's status as a leading maize exporting country. The crop is influenced by climate variation and demands a uniform temperature in the range of 21–30 °C, accompanied by a 50–100 cm of rainfall. The result of regression of the keys influencing its production is highlighted in Table 6 (column 2). While increasing maximum temperature presents a positive impact on maize production, increasing minimum temperature influences the production in negative way. The 1% increasing of maximum temperature is increasing the maize production as 1.8224% ($p < 0.1$), while 1% increasing of minimum temperature is decreasing the production as 0.7845% ($p < 0.1$). The value of squared R equals to 0.689 that is explaining the existence of 73.71% variation inside the modelling. The findings indicate that a growth in the area of forest exerts a negative impact on the yield of maize. The 1% increase in the area of forest leads to a fall of 0.1841% in production ($p < 0.1$). It implies the need to compromise the forest area land for growing the required volume of maize and overcoming the paucity of its cultivation area, hence corroborating the experience of Brazil associated with the ongoing rate of deforestation (USITC, 2011). Moreover, there is a significant positive impact of the irrigated area on the production of maize. The 1% increasing of the area gross irrigated will be resulting in a 0.194% increasing in the yield of maize ($p < 0.01$), providing evidence in support of the second hypothesis. Given that maize productivity in Ethiopia is mainly associated with rainfall and growing 1 kg of maize requires higher than 2–3 L water per day (Ben-Ari et al., 2016), there is a big potential for growing maize utilizing the techniques of irrigation and protecting the crop from the influence of droughts. Thus, the more the area irrigated, the greater will be the maize cultivation area exposing to water, resulting in higher production. Because of the population boom and the increase in pressure on arable land, there is existence of a serious

Table 7
Maize, Sorghum, Barley, and Wheat estimation results table.

Variables	Ln (Maize)	Ln (Sorghum)	Ln (Barley)	Ln (Wheat)
Ln (GA)	0.205***	−0.0606	0.2667***	0.2009***
	(0.0384)	(0.0504)	(0.0290)	(0.0511)
Ln (TR)	−0.0201	−0.0388*	0.0355	−0.1686**
	(0.1724)	(0.0710)	(0.0273)	(0.0718)
Ln (AW)	0.3302***	0.0719	0.0805	1.212***
	(0.1623)	(0.1443)	(0.0687)	(0.1033)
Ln (HP)	−0.03669	0.0169*	0.0955*	−0.1921
	(0.2566)	(0.0274)	(0.0505)	(0.1354)
Ln (FC)	0.6922*	0.2009	−0.0729	0.0156*
	(0.4724)	(0.1353)	(0.0999)	(0.1324)
Ln (FA)	−0.1943*	0.9208***	−0.1138***	−0.9339***
	(0.0862)	(0.1459)	(0.0356)	(0.0696)
Ln (RF)	0.0013*	−0.1553*	0.311***	0.0203
	(0.1823)	(0.0672)	(0.0560)	(0.0823)
Ln (MIN)	−0.8279*	−0.0460	0.3904**	0.2622*
	(0.6486)	(0.1214)	(0.1784)	(0.2154)
Ln (MAX)	1.9234*	0.0580	0.4482	−0.4482*
	(1.5106)	(0.1214)	(0.2943)	(0.2714)
Constant	−4.3109	6.3991***	1.9378	2.9849*
	(4.8186)	(2.0219)	(1.2996)	(1.4408)
Year Dummies	Yes	Yes	Yes	Yes
Observations	64	41	88	70
Number of groups	7	5	9	7
R-squared	0.7411	0.9801	0.8367	0.9917

Note: The numbers in parentheses represent standard errors and "*, **, ***" are statistical significance at the level of 10%, 5%, and 1% level.
Source: Authors' own calculations.

food and cash crops shortage. Since maize is mainly a commercial crop that bears the load of the farming industry expanders in Ethiopia, it is essential to raise its production for addressing the shortage caused by the decline in productivity between 20% and 43% during 2014–2021 (CSA, 2021). The climate change and farmers' shift from producing maize to other relatively easy to produce, e.g., soybean, contribute to the ongoing declines. Hence, people's involvements in agriculture represent a main key for the maize production and this is corroborated by a relevant finding of this study, i.e., the 1% increasing of workers in the agriculture sector will lead to 0.3129% increasing of the yield of maize ($p < 0.1$).

The next crop for investigation is barley, i.e., a cereal crop that grows in the sub-tropical and the tropical regions of Ethiopia, e.g., Oromia, Amhara, Tigray and southern nation nationality and Regional State. Cultivation of barley necessitates a mild winter climate and grows best in climates such as dry and cool rather than hot and moist ones. Since it is highly responsive to changes in temperature and precipitation, we investigate the effect of climatic change and other keys impacting the barley's cultivation and yield. Table 7 (column 4) is showing the results of our analysis for barley. The estimation results reveal that an increase of the temperature in minimum is positively influencing the production of barley. The increasing of 1% temperature in minimum is increasing of 0.3699% the production ($p < 0.05$). Since the production of barley is in characterized climate of dry and cool, an increasing of the temperature in minimum will turn more suitable the climate for higher production of yields. The value of squared R equals to 0.8321 explains an existence of 83.21% change in the modelling. The yearly rainfall and irrigated gross area are as well significant keys influencing in positive way the barley production. A 1% increasing in the two is increasing by more than 0.25% the production ($p < 0.01$). Barley grows in rainfall dominated regions. Therefore, the regions that are suffering from less frequent and/or low levels of rainfall rely completely on irrigation techniques. On the consumption side, the boom of population has incremented the crop's demand, especially from people living in the sub-tropical and the tropical national regions. This backdrop necessitates a higher barley area of cultivation that can uniquely be realized through the compromise of the cover of forest. We find that an increasing 1% of the area of forest is leading to a decline of 0.1079% in the barley production. Therefore, it exists a hold of a negative relation among yield of barley yield and area of forest.

We have now the wheat as the last crop for our analysis. The global wheat production amounts to an annual average of about 750 million tons (t) (2016–2018, OECD, 2022). More than two-thirds of this volume is used for food and one-fifth is used for livestock feed, altogether addressing the need of approximately 35% of the global population (Grote et al., 2021). In Ethiopia, wheat is the third most dominant crop after teff and maize, grown mainly in Oromia, Amhara, SNNPR, and Tigray regions. It is a rabi crop which necessitates rainfall from 50 to 100 cm and a temperature ranging between 14 and 18 °C (Mohammed et al., 2022). Table 7 (column 5) provides us the relative wheat results of estimation. The increase of temperature in minimum positively influences the production in positive way and the parameter for temperature in minimum is significant. The high extreme temperatures influence the wheat production in negative way and the findings show a significant effect of the temperature in maximum on the wheat production. The R squared value of 0.9863 explains the existence of 98.63% change in the modelling. The change in area of forest influences the production of wheat in negative manner, e.g., the 1% increasing of area of forest is leading to decreasing the productivity by 0.8849% ($p < 0.01$). The worker number is affecting the production positively, e.g., the 1% increasing the number is leading to increasing the production by1.149% ($p < 0.01$).

Though Ethiopia has emerged like an economy based on agriculture in which it exists a higher dependence on the tractor utilization, machinery and technologically advanced implementation, some states sinking in poverty do not access to all of these. These states have dependence on crops that are labour intensive, implying a possibility that an increase in labour will lead to an increase in the wheat production. The results corroborate hypothesis 2, given that the increasing 1% of the irrigated gross area is resulting in an increasing of the yield of wheat by 0.1904% ($p < 0.01$). This is justified by the issue of shortage in water that Ethiopian regions face. The climate's gradual variations are resulting in the changes of precipitation and hence, increasing the area of irrigated lands and lessening the rainfall reliance will be increasing the wheat production. The consumption of fertilizer in total is also an important variable which is influencing the production of wheat in positive way as the parameter is significant ($p < 0.1$).

Now, we investigate the impact of these keys of productivity on the overall crops production in Ethiopia. Table 7 indicates the estimation results of the investigation. While price of harvest in farm, area of forest, area irrigated and temperature in maximum are related to the yield of agriculture in negative manner, keys such as temperature in minimum, rainfall, tractors number, workers in agriculture, and consumption of fertilizer present a positive impact on agriculture production in Ethiopia. Table 8 demonstrates the impact of the variables under study on the country's overall yield. The square R value is 0.8216 explaining the presence of 82.16% change in the modelling. The increasing 1% of the temperature in maximum is resulting in the decline by 0.4130% of the production in total ($p < 0.1$). Lately, Ethiopia experiences hotter temperatures and different levels of precipitation.

The farm activities mainly relying on rainfall until today. The interpreted results approve that farm activity in Ethiopia is related to monsoon positively. The increasing 1% of the rainfall leads to a decline in the production of 0.1693% ($p < 0.01$). In Ethiopia, the monsoon is a main key to determine the yield's quality and quantity. The regular intervals between rainfall keep the moisture of soil and diminishes the crops production costs consequently conducting to a reliance that is lower for the systems of irrigation. Though techniques of irrigation become famous on the date, a large section of farmers who are small and marginal ones in Ethiopia do not find affordability for irrigation. This brings increase to a negative impact of irrigated gross area on production of crop. Given the findings, the increasing 1% of the irrigated gross area is leading to a decline in the yield of agriculture in total in Ethiopia by 0.2756% ($p < 0.01$). The systems of irrigation installation, canals creation, farmers' applied training are involving a high volume of

Table 8
Overall yield productivity estimation results.

Variables	Ln (Yield)
Ln (HP)	−0.0711*
	(0.0384)
Ln (FA)	−0.0838**
	(0.0400)
Ln (GA)	−0.2908***
	(0.0647)
Ln (MIN)	−0.1453
	(0.1103)
Ln (MAX)	−0.4358*
	(0.2093)
Ln (RF)	0.1786***
	(0.0507)
Ln (TR)	0.0612
	(0.0391)
Ln (AW)	0.1341***
	(0.0456)
Ln (FC)	0.2031***
	(0.0633)
Constant	12.949***
	(1.2934)
Year Dummies	Yes
Observations	88
Number of groups	9
R-squared	0.8361

Notes: The numbers in parentheses represent standard errors (SE).
*, **, *** are statistical significance at the level of 10%, 5%, and 1% levels, respectively.
Source: Authors' own calculations.

investments via the government which will eventually increase the crops' production costs (Workneh et al., 2021). Consequently, it turns out to be higher production in areas of rain-fed compared to the areas irrigated in the not advanced states in agriculture involving in farm activity and thus a stronger positive relationship to rainfall than irrigation. The area of forest presents a negative effect on production in total. The yield's fall of 0.0794% is resulting from an increasing of the cover of forest by 1% ($p < 0.05$). This is justified by the limit in land availability to grazing and cultivation. The higher the forests' area, the lower will be the availability of land to agriculture productivity.

The findings indicate that for the goal of increasing crops production more land is needed to be cultivated. In accordance with FAO (2016), agricultural activity is the main reason to reduce the area of forest. Roughly 30–40% of Ethiopia's rapid growing agriculture sector during 2004–2014 is the result of using fertilizers in higher quantity. The Ethiopia's revolutionary act in the sector of agriculture sector brought approximately a positive change in the crops production. Following the study of Rashid et al. (2013), there is increase in fertilizer use by 60% from 2007 to 2012. This is also thanks to the growth needs for crops of food through the burgeoning Ethiopian population. While the regions such as Amhara, Oromia, SNNP and Tigray necessitate greater fertilizer consumption due to the type of soil and cultivated large area, other regions such as Afar, Somali, Gambella, and Harari present a low consumption. The fertilizers' adequate amount is leading to rise in the soil efficiency. The results of estimation show evidence that the hypothesis 1 is correct. With the consumption in fertilizer increasing 1%, an increasing in the yield will be by 0.1925% ($p < 0.01$). Ethiopian land is suffering from degrading soil and deficient nutrients which is reinforced via fertilizers. For boosting the soil's fertility and to promote greater yield, we require a higher organic manure and fertilizers (Līcīte et al., 2022). The workers in agriculture present a positive influence on the production. A rise in the workers' number is leading to a yield increase of 0.1271% ($p < 0.01$). The workers in agriculture in Ethiopia are evidenced as more productive compared to advanced machines using and implementations. Whereas the intensive labour in farm is generally not big and is not contributing much to the country's income. It is because, the sector of farm in Ethiopia is reputed by its high disparity of farmers between very small and rich. Therefore, the needed requirement is to use more workers in the economy's essential sector, i.e., agriculture, for increasing the crops productivity. Finally, it is valuable mentioning that increasing the price of harvest is leading to the decrease in the crops production. We expect that an increasing of 1% for the price of harvest in farm leads to the yield decrease by 0.0674% ($p < 0.1$). The rapid pace of urbanization and industrialization offers different advanced techniques in increasing the production. Nonetheless, the Ethiopia's landholdings are the ownership of farmers who are small and marginal. The poverty statues of the Ethiopian economy are making the utilization of high yielding varieties of seeds, pesticides and fertilizers hard for a large section of farmers. The absence of training on the use of the contemporary methodologies adds to the expenses, turning the productivity to cost high and less affordable, leading to subsequent decline in the production of crops and loss of the farmers.

4.3. Robustness checks

We proceed by performing a set of robustness tests to probe the robustness of these results. Tables 9–11 present the estimated effects of crop yield productivity in various types of robustness analyses. Each one represents a separate regression result for the impact variables or factors on productivity of crops using alternative lag data.

Changes in the lag structure (2- or 5-year lags instead of 1 year) of the input factor variables do not alter the main findings. For the Cobb-Douglas model, changes in the lag structure do not significantly result in changes in the sign of the coefficient, and the estimated coefficients remain significant in all cases. The model sign and size of the coefficients are similar to the baseline results. In particular, coefficients are similar and significant in the case of 2-year lags but smaller and sometimes insignificant in the case of 5-year lags. Hence, our main findings seem to be quite robust to the inclusion of up to 5-year lagged factors of crop productivity (see Tables 9 and 10 for the coefficient estimates with 2- and 5-year lags). With 2-year lags, the data are affected by the business cycle more while it has more observations; with 5-year lags, the data are affected by the business cycle less while it has fewer observations. With

Table 9
Robustness analyses: estimated impact of climatic change on agriculture production (alternative lag data (2-year lags)).

Variables	Ln (Maize)	Ln (Sorghum)	Ln (Barley)	Ln (Wheat)
Ln (GA)	0.179***	−0.0530	0.2335***	0.1759**
	(0.0375)	(0.0491)	(0.0283)	(0.0490)
Ln (TR)	−0.0176	−0.0340**	0.0311	−0.1476***
	(0.1682)	(0.0693)	(0.0267)	(0.0700)
Ln (AW)	0.2891**	0.0630	0.0705	1.061**
	(0.1584)	(0.1408)	(0.0670)	(0.1008)
Ln (HP)	−0.03213	0.0148***	0.0836***	−0.1682
	(0.2247)	(0.0240)	(0.0492)	(0.1321)
Ln (FC)	0.6062**	0.1759*	−0.0638	0.0136*
	(0.4608)	(0.1320)	(0.0975)	(0.1292)
Ln (FA)	−0.1701	0.8064**	−0.0997***	−0.8178**
	(0.0841)	(0.1423)	(0.0347)	(0.0679)
Ln (RF)	0.0010**	−0.1360*	0.272**	0.0178
	(0.1779)	(0.0656)	(0.0546)	(0.0803)
Ln (MIN)	−0.7250**	−0.0402	0.3418*	0.2296*
	(0.6327)	(0.1184)	(0.1740)	(0.2101)
Ln (MAX)	1.6843***	0.0508*	0.3925	−0.3925**
	(1.4736)	(0.1184)	(0.2871)	(0.2647)
Constant	−3.7750*	5.6037***	1.6970*	2.6139*
	(4.7005)	(1.9720)	(1.2677)	(1.4054)
Year Dummies	Yes	Yes	Yes	Yes
Observations	42	27	58	46
Number of groups	7	5	9	7
R-squared	0.5758	0.8260	0.5636	0.8724

Note: Numbers in parentheses represent standard errors and "*, **, ***" indicate statistical significance at the level of 10%, 5%, and 1% level.
Source: Authors' own calculations.

Table 10

Robustness analyses: estimated impact of climatic change on agriculture production (alternative lag data (5-year lags)).

Variables	Ln (Maize)	Ln (Sorghum)	Ln (Barley)	Ln (Wheat)
Ln (GA)	0.185***	−0.0549	0.2420***	0.1823*
	(0.0308)	(0.0509)	(0.0294)	(0.0517)
Ln (TR)	−0.0182*	−0.0352***	0.0322	−0.1530***
	(0.1743)	(0.0718)	(0.0276)	(0.0725)
Ln (AW)	0.2996*	0.0653	0.0730	1.100**
	(0.1641)	(0.1459)	(0.0694)	(0.1044)
Ln (HP)	−0.03330	0.0154**	0.0866**	−0.1743
	(0.2329)	(0.0249)	(0.0510)	(0.1369)
Ln (FC)	0.6281***	0.1823**	−0.0660	0.0140***
	(0.4775)	(0.1368)	(0.1010)	(0.1336)
Ln (FA)	−0.1763***	0.8356**	−0.1033**	−0.8475**
	(0.0871)	(0.1474)	(0.0360)	(0.0703)
Ln (RF)	0.0013*	−0.1409*	0.202*	0.0184
	(0.1843)	(0.0680)	(0.0566)	(0.0832)
Ln (MIN)	−0.7513**	−0.0417	0.3542***	0.2380**
	(0.6556)	(0.1227)	(0.1803)	(0.2177)
Ln (MAX)	1.7453***	0.0526	0.4067	−0.4067***
	(1.5270)	(0.1217)	(0.2875)	(0.2643)
Constant	−3.9119	5.8069***	1.7585***	2.7089**
	(4.8709)	(2.0438)	(1.1335)	(1.4564)
Year Dummies	Yes	Yes	Yes	Yes
Observations	38	22	50	41
Number of groups	7	5	9	7
R-squared	0.5896	0.8215	0.6448	0.8547

Note: Numbers in parentheses represent standard errors and "*, **, ***" are statistical significance at the level of 10%, 5%, and 1% level.
Source: Authors' own calculations.

Table 11

Robustness analyses: estimated impact of climatic change on agriculture production (translog production function).

Variables	Ln (Maize)	Ln (Sorghum)	Ln (Barley)	Ln (Wheat)
Ln (GA)	0.237**	−0.0703	0.3099**	0.2335***
	(0.0497)	(0.0652)	(0.0376)	(0.0662)
Ln (TR)	−0.0234	−0.0451*	0.0413	−0.1959**
	(0.2232)	(0.0919)	(0.0354)	(0.0929)
Ln (AW)	0.3837***	0.0836***	0.0935***	1.409***
	(0.2102)	(0.1869)	(0.0889)	(0.1338)
Ln (HP)	−0.04264	0.0197***	0.1109**	−0.2232
	(0.2982)	(0.0318)	(0.0653)	(0.1753)
Ln (FC)	0.8044**	0.2335*	−0.1038	0.0221**
	(0.7498)	(0.1752)	(0.1293)	(0.1714)
Ln (FA)	−0.2257**	0.9700**	−0.1323***	−0.9852***
	(0.0910)	(0.1888)	(0.0461)	(0.0901)
Ln (RF)	0.0016***	−0.1805*	0.361***	0.0236
	(0.2360)	(0.0870)	(0.0724)	(0.1065)
Ln (MIN)	−0.9621**	−0.0534	0.4536**	0.3047**
	(0.8396)	(0.1572)	(0.2309)	(0.2788)
Ln (MAX)	2.2350***	0.0674	0.5208	−0.5208**
	(1.9553)	(0.1572)	(0.3810)	(0.3513)
Constant	−5.0092**	9.1193***	1.5352*	4.2538*
	(7.6495)	(2.6171)	(1.6822)	(1.8650)
Year Dummies	Yes	Yes	Yes	Yes
Observations	64	41	88	70
Number of groups	7	5	9	7
R-squared	0.7831	0.9840	0.8857	0.9915

Note: Numbers in parentheses represent standard errors and "*, **, ***" indicate statistical significance at the level of 10%, 5%, and 1% levels.
Source: Authors' own calculations.

different data lags, the estimated relationship between climate change and agriculture production is generally robust.

The results discussed so far assume a Cobb-Douglas gross output production function in estimating crop productivity. In order to allow for more flexibility, we consider a translog production function, where output may depend non-linearly on input factors. It is more flexible, as output elasticities are not specific to factors but vary across crops and times. Table 11 presents regression results for the impact variables or factors on productivity of crop using translog production function, which are broadly consistent with the ones obtained when assuming a Cobb-Douglas production function. As a second robustness check, the results confirm our main findings and remain robust.

5. Discussion of results

The increase in level of shocks of climate throughout Ethiopian economy has impacted production of food in several ways, i.e., indirectly and directly. Important alterations in the cycle of productivity and the ecosystem of agriculture are the known direct effects of these variations in climate. However, the impact on the crops' demand that affects the growing economy can be considered as an indirect effect. The prices of agriculture present an indirect main effect because of shocks in climate, not only for Ethiopia but also for the whole world. The World Bank data predicts a steep increase in prices of agriculture, i.e., an increase of 18%, 24% and 78% for the world, South Asian and Sub-Saharan Africa (SSA) economies, respectively (World Bank, 2021). Consistent to these predictions and rising distortions in the stability of climate, the upward pressure on prices of agriculture worldwide, particularly in Ethiopia having most of the population living under poverty line, poses a challenge to mass food security.

The analysis of the research shows a negative association between the temperature in maximum and the respective crops' production of agriculture in overall. For a 1% increase in the temperature in maximum, the overall production declines by 0.4130%. The productivity and transpiration of soil are susceptible to disrupt because of the rainfall fluctuations and the temperature in maximum rising. In addition, given the extremely unsuitable conditions of weather in the nation, there are great possibilities of infertility of soil which leads to a fall in the crop's quality and quantity (Kome et al., 2018). The research reveals that a temperature increase is expecting to raise the land degradation's risk which turns it not suitable to productivity of agriculture. This aligns with the finding of UNCCD (2021) that revealed an estimated loss of 12 million ha of agricultural land leading to a potential loss of at least 20 million t of grain per annum. The findings of the present research also show a positive impact on the whole production by rainfall. A 1% increase in the rainfall leads to an increase in the crops' yield by 0.1693%. This result exerts a positive impact on the security of food. A rainfall increase will be leading to surplus in the food and cash crops productivity. As rainfall represents a seasonal event, the government is not able to regulate it. In order to increase the water supply, the government of Ethiopia must concentrate on the development of advanced systems of irrigation for minimising the farmers' dependency on rainfall. The government already started implementing different policies and schemes for reducing the impacts of climatic change and low production on security of food. Following our understanding of the interconnectedness among climatic change, production of agriculture and security of food, and look in the shaped policies of government for addressing the future challenges in Ethiopia, we switch to the following paragraph with an intention to offer essential strategies of mitigation and adaptation for tackling climatic change and insecurity of food. In order to address the variety of challenges facing the economy of Ethiopia, involving low production of the sector of agriculture, poor health, lack of infrastructure, threat in wildlife and forests, rising sea levels, growing population pressure on land and absence of government support on technological applications, active presence of private and public companies is vital. In this specific reasoning, we would currently want to illustrate in a concise manner the variety of policies of mitigating climatic change that the Ethiopian government formulates with the help of the WHO and the UNICEF.

The major problems we highlight in the paper, i.e., climatic change, security of food, are associated mainly with production of agriculture. Given the ongoing population growth and the country's resource constraints, we require an immediate expansion in the volume of production. Advanced techniques in farm must be employed to counteract the shocks of climate. Improved systems of irrigation must be introduced to support cultivation of various kind of crops that are insensitive to the changes in climate. Academic scholars such as Li et al. (2002), Yadav et al. (2024), and Batima et al. (2005) emphasised that the improvement in the capacity adaptation in response to the changes in agricultural practices, crops and livestock upgrade through breeding and spending on modern infrastructure and know-how are of utmost importance. The authors have stressed that those procedures would turn the grassland adaptation with the current conditions of environment and also the practice of reasonably rotational grazing possible, while ensuring sustainability of the grassland resources. Further, it is considered pertinent to increase in the size of land hold for the farmers and enhance the cultivation area. Particular focus must also be accorded to the advancement of infrastructure in states that are prone to natural calamities, e.g., droughts and floods (Faye, 2022). In addition, the increase of the awareness of farmer through purpose-built educational programmes in villages that are rural may also be of use as a step towards making successful technological progress. Also, in accordance with the Fourth Assessment Report of the IPCC et al. (2007), new plans of contingency must be implemented for developing awareness related to the occurrences of natural calamities between the workers with lower skills and for preparing these latter to migrate and adapt if an emergency case is about to happen. Policies in agriculture must be formulated towards promoting organic farming, and hence reducing the impact of agricultural activities on climate and ensuring greater profits and yields (Līcīte et al., 2022). In accordance with the FAO (2022), the genetically modified (GM) crops that have the capacity to face natural occurrences and climate shocks, and as result increase the food productivity in a sustainable manner should be planted. As Klümper and Qaim (2014) revealed in light of an analysis of over one hundred studies, GM crops bolstered crop yields by 22% and farmer profits by 68%, based on reduced application of pesticide by 37%.

In Ethiopia, the growth in agriculture has resulted in a decline of 33% in the share of people living under poverty, from 2000 to 2011 (World Bank, 2021). In this study, the estimation results show that a 1% increase of workers in the agriculture sector will lead to 0.3129% increase of the yield of maize, corroborating the notion that workers in agriculture affect the maize productivity in a significant manner. On the contrary, in light of the large economic migration of population from rural to urban areas, there is a rising concern that decline in the availability of labour in both short- and long-term periods may endanger agricultural production, resulting in national food security (Balwinder-Singh et al., 2020). For instance, the statistics of the Ethiopian Government show a decline in the maize productivity of 20%–43% during 2014–2021 (CSA, 2021). This fall is caused by climate change and the shift from maize productivity to other crops productivity by the farmers because the other crops are easier in production. Some of the laborers in agriculture who cultivate the maize made a shift to the productivity of soybean that now brings 18% to the country's total productivity of oil crop (CSA, 2021). Hence, workers in agriculture represent a main key for the production of maize and, likewise, other staple crops. However, given that consumption largely outpaces production of the staple crops, and turns the Asian and African into major net importers (Grote et al., 2021), the Ethiopian government needs to develop a smooth food distribution system to ensure availability of food for people living in poverty at subsidized rates. More reliable planning and execution through the agencies of government are required to reduce levels of poverty. Generation of more jobs and increase in the minimum wage rate are also required to ensure sufficiency of household income towards meeting their basic needs of food intakes. The government needs to provide security in finance and reduce the gender gap, motivate females to join the agricultural workforce, and offer rural poor opportunities and jobs of better standards to decrease the number of people migrating from rural to urban areas.

Climate in Ethiopia is very sensitive to variations in weather and therefore, it is prone to diseases' transmission. IPCC (2017) and FAO (2017) report the presence of a risk of rising vector-borne diseases such as diarrhoea, dengue and cholera, as a consequence of the climatic fluctuations. The government of Ethiopia is therefore obligated to address the needs of people having no access to appropriate health facilities and make more investments on developing hospitals and monitoring enforcement of regulations related to unpaid check-ups of health in urban and rural poor. Furthermore, based on the report of climate change and health of the Ministry of Health of the Government of Ethiopia (2022), and the National Meteorological Agency (NMA) of Ethiopia, it will be very useful to construct predictable indicators of risk of climate sensitive diseases like Chikungunya, Dengue Fever, yellow fever, Malaria, West Nile Virus, Tick-borne Encephalitis, and Lyme disease, and waterborne diseases such as cholera and diarrheal diseases, and launch awareness development and support programmes.

There is strong nexus between the forests and the production of agriculture. The promotion of afforestation and preservation of habitat of nature will not only diminish the global warming possibilities via the decrease of levels of pollution but will also give fuel and other benefits to the population in rural, hence, we will see their income and living standard increase (Hasan et al., 2023). Programmes that help the prevention of deforestation and fires in forest must be enacted for improving the use of land and increasing agriculture land's sustainability, as noted in the Fourth Assessment Report of the IPCC et al. (2007). To that aim, supportive programmes should be initiated for conserving, and ameliorating the livelihood of population living in the forest area and its peripheries. In addition to this, given that Africa has the largest area of arable uncultivated land in the world (202 million hectares) and, on the contrary, farms in general only hold less than 2 ha (Africa Competitiveness Report – WEF, 2015), land governance needs to be revisited to ensure higher land holdings by farms. Moreover, easy access to finance needs to be provided and an integration of smallholder farmers into larger cooperatives and groups needs to be coordinated using government support. Rural infrastructure needs to be improved to connect these evolving cooperatives/groups with wider markets while minimising the influence of intermediaries.

The Ethiopian agricultural sector is largely dependent on groundwater for irrigation purposes. The growth of population raises pressure on the land for cultivation because of the request for a higher yield even though the limits in resources possessed by a country like Ethiopia. This results in non-renewable water overexploitation, which makes it not accessible and difficult in reaching to farmers who are marginal and small (Dhifaoui et al., 2023). So, the need for the formulation of techniques and plans for the conservation of water, particularly in the areas that are struggling due to shortage of water. For example, the advances in systems of irrigation and in tube wells should be installed in most of the villages in order to counteract the scarcity of water. Given that some regions in Ethiopia are greatly endowed by rainfall surplus (World Bank, 2021), the Ethiopian government should corroborate the Ministry of Water and Energy and the National Meteorology Agency to install provisions to re-direct the surplus from rainfall to artificial storage of groundwater, so that water shortage in both urban and rural areas can be mitigated through an organised redistribution system. Moreover, there is a significant positive impact from area irrigated to production of maize. The 1% increase in the gross irrigated area will be resulting in a 0.194% increase in the yield of maize ($p < 0.01$). This provides evidence for the second hypothesis which indicates an increase of the irrigated area would lead to higher crops production. This also corroborates the finding of the Africa Competitiveness Report (WEF, 2015) that suggested that irrigated farms manage 90% higher average yields than those of the rain-fed farms in the nearby areas.

6. Conclusion

This study documented the interconnectedness among changes in climate, security of food and agriculture, and concentrate on how the prior changes bring the latter kind of alterations. The study also involves different keys in addition to the production of agriculture that are leading to the insecurity of food and emphasises the main challenges that are facing the population in the rural and urban areas, given the variations in climate. For our empirical investigation, we have used a dataset collected based on a variety of legal sources. In order to assess the repercussions of the climatic change on production of agriculture, four staple crops containing both food crops and cash crops were considered. We have chosen the crops based on their significance and dominance as sectors of agriculture in Ethiopia. We took the size of the country and the agriculturally rich regions of Ethiopia into consideration while conducting the investigation. It implies that this study has not covered all nine regions of Ethiopia due to the extreme climate conditions in some regions which in turn might be resulting in biased and erroneous results. For estimating the effect of climate shocks on the production of crops, different keys impacting production were accounted as the independent variables whereas the kilogram per hectare yield was taken into account as the explained variable. We apply the Cobb Douglas function of productivity in our estimation analysis. Additionally, in the econometric model, we employ the linear regression analysis-based panel corrected standard errors for eliminating both the multicollinearity and heteroskedasticity risk.

We can sum up our findings by revealing that agriculture in Ethiopia is prone to changes in climate and variations in the levels of precipitation. The majorly impacted crops through changes in meteorology are sorghum and barley. Furthermore, we make the link of correlation between the climate changes and security of food, hence and show that the adverse effects on stable crops' production like barley has resulted in insecurity of food in Ethiopia. We have recommended some policy implications and adaptations for mitigating these effects of climate change on production of agriculture and security of food in Ethiopia.

Once we understand the interconnectedness among climatic change, agricultural production, and food security, and look in the government policies for addressing the future challenges in Ethiopia, we recommend some policy implications and adaptations for mitigating the effects of climate change on the production of crops and food security in Ethiopia.

First, given the rising population growth and scarcity of the country's resources, an immediate enhancement in the levels of production is warranted. Advanced techniques in farm must be employed to counteract the shocks of climate in an effective manner. For example, improved systems of irrigation must be brought into cultivating various kinds of crops which are insensitive to the changes in climate. Further, it is pertinent to improve the land governance and ownership in order to raise the size of arable land holding of the farmers. Policies need to be formulated for promoting organic farming towards reducing the impact of agriculture on climate and sustaining profits and crop yields. Capacity to face natural occurrences and climate shocks needs to be installed while carrying out genetic modification of the plants, and as a result minimising influence of climate on the food productivity. Further, effective plans need to be formulated for the conservation of rainwater and redirection of the surplus to the water lacking regions. The workers need to be educated and trained to face the challenges of tillage development and employment of tractors in the right parts of agriculture and in the right kind of soil to enhance the crop and soil production and minimise degradation of soil.

Second, it is evident that historically the growth of agriculture contributed to the decline in the share of people living in poverty. However, the need for an advancement with regards to the living standard still persists. Effective planning and execution need to be made through the government agencies in order to provide financial security to farms, create sector-specific job opportunities with a guaranteed minimum wage rate, motivate females to participate in agricultural workforce, resulting in a reversal of the workers' economic migration from rural to urban areas. In complement, the government needs to put a smooth food distribution system in place, ensuring availability of staple food at a subsidized rate.

Third, contingency plans must be made for building workers' awareness regarding natural calamities and the precautions to take to encounter emergencies arising from these. Further, given that variations in weather and calamities accompany vector-borne diseases such as diarrhoea, dengue and cholera, necessary investments will be required to establish hospitals or village clinics for free consultations and health check-ups in order to address the needs of the poor people having no access to appropriate health facilities. In complement, it will be very useful to develop indicators of sensitive diseases like Chikungunya, Dengue Fever, yellow fever, Malaria, West Nile Virus, Tick-borne Encephalitis, and Lyme disease, and waterborne diseases such as cholera and diarrheal diseases, and make people aware for early detections.

Fourth, it is evident that there is a strong nexus between forests and the production of agriculture. Programs and regulations that help the conservation of forests, prevention of fires in forest, promotion of afforestation and preservation of habitat of nature need to be enacted to not only decrease pollution levels of pollution but also ameliorate the livelihood of people living in the forest peripheries. In order to enhance the productivity of land and likewise the crop yields while conserving forests, widescale mechanization in the forms of modern irrigation facilities and use of tractors, applications and availabilities of organic fertilisers and GM plant seeds, widescale training and awareness programmes, and so on, will be required.

Compliance with ethical standards

Not Applicable.

Statement of human rights

Not Applicable.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CRediT authorship contribution statement

Ahmed Bouteska: Writing – review & editing, Software, Methodology, Formal analysis, Conceptualization. **Taimur Sharif:** Writing – review & editing, Visualization, Validation, Supervision, Methodology. **Faruk Bhuiyan:** Writing – review & editing, Visualization, Resources, Investigation. **Mohammad Zoynul Abedin:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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