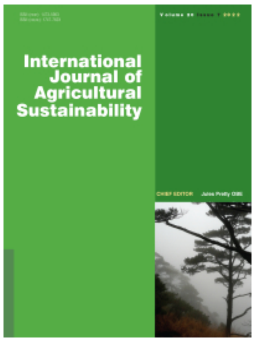

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Exploring climate change resilience of major crops in Somalia: implications for ensuring food security

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ABSTRACT

The complex relationship between climate change and major crop output poses urgent challenges for contemporary food production systems. Recognizing the diverse responses of different crops to climatic stressors, it is necessary to investigate the repercussions of climate-induced shifts in various crop yields. Focused on the adverse extreme weather impacts on food security, this research employs multiple specifications to assess the effects of climate change on major crops—maize, sorghum, rice, wheat, sugarcane, bananas, and beans—in Somalia using annual data spanning 1991–2019. The empirical findings from the autoregressive distributed lag (ARDL) approach reveal that increasing precipitation positively impacts the long-run output of sorghum, sugarcane, and banana while adversely affecting bean production. Conversely, changing temperatures detrimentally affect the long-run output of sorghum, rice, and beans, although they enhance rice and sorghum production in the short-run. Intriguingly, the study reveals that greenhouse gas (GHG) emissions and crop-harvested areas significantly enhance the yields of various crops. Moreover, agricultural labour positively impacts bananas while hampering other crop outputs. Based on these results, the study proposes the adoption of climate-resilient crop varieties, investment in irrigation infrastructure, enhanced weather prediction and early warning systems, as well as the promotion of sustainable land management.

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Climate change; major crops; food security; environmental degradation; crop production; Somalia

1. Introduction

The increasingly unpredictable climatic conditions became the primary source of risk for sustaining global food security. The major culprits of global warming are unequivocally unresolved anthropogenic activities such as deforestation, GHG emissions, land use changes, urbanization, as well as patterns of consumption and production across regions (Abbas & Mayo, 2021; Abdi, 2023; Rehman et al., 2022; Warsame et al., 2023). The concentrations of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and water vapour are some of the GHGs that are emitted into the atmosphere as a result of burning fossil fuels and other human-induced processes, raising ecosystem concerns (Janjua et al., 2014). These pollutants persistently change the temperature and precipitation patterns, which has a harmful influence on water, land resources, health, and agricultural output (Yurtkuran, 2021). According to the Intergovernmental Panel on Climate Change (IPCC) (2022), the earth's surface temperature rose by 1.1 °C between 2011 and 2020, above the average of the industrial age from 1850 to 1900. In recent years, climate change has led to an increase in the frequency of natural catastrophes such as droughts, floods, cyclones, and heat waves, all of which have a negative impact on the functioning of ecosystems, infrastructure, water resources, and human health (Birthal et al., 2014; Hossain et al., 2019). The global economy suffers greatly as a result of these

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developments, which may eventually exacerbate rural poverty, food insecurity, and social instability (Abdi et al., 2023a). Because of this, adaptive measures can lessen climate change susceptibility by improving rural populations' resilience, enhancing crop varieties, and mitigating possible harm (Chandio et al., 2020).

Compared to other industries, climate variability has most drastically influenced agricultural output because of its higher sensitivity (Chandio et al., 2021). Numerous factors, such as changes in rainfall patterns, rising temperatures, soil moisture, the hydrologic cycle, and evapotranspiration, affect the types of crops grown and the timing of planting and harvesting (Abbas, 2022; Ben Zaied & Ben Cheikh, 2015; Chandio et al., 2021; Janjua et al., 2014; Jayathilaka et al., 2012). While some evidence suggests that rising temperatures can increase crop yields by speeding up photosynthesis, most empirical studies indicate that higher temperatures reduce essential plant components like vitamin B, protein, and micronutrients (Abbas & Mayo, 2021; Ozdemir, 2022). According to Warsame et al. (2022), dry periods caused by climate variability not only make crop cultivation more challenging but also negatively affect the nutritional quality of the crops. In addition, harsh weather events like floods, dry spells, and variations in the geographical and seasonal distribution of precipitation further compound the issue (Dubey & Sharma, 2018; Ngoma et al., 2021). Increased rainfall intensity is expected to accelerate soil erosion, posing additional risks to agricultural yields (Adhikari et al., 2015). These extreme weather events have become more frequent and intense, leading to significant reductions in crop harvests in developing countries (Abdi et al., 2023b). Besides, rising temperatures and evapotranspiration have an indirect multiplier effect on crop yield, which increases the amount of water needed for agricultural production (Ben Zaied & Ben Cheikh, 2015; Chandio et al., 2022; Pickson et al., 2020; Warsame et al., 2022). It is notable that the lack of a corresponding increase in precipitation can lead to major crop failures in many areas.

Two-thirds of the calories humans consume come from food grains like wheat, rice, maize, and soybeans (Zhao et al., 2017). The primary risk factor for food security and agricultural systems is climatic variability, which includes rising temperatures, shifting rainfall patterns, increasing sea levels, floods, and droughts (Chandio et al., 2020). These fluctuations have led to strained water supplies, glacier melting, and increased occurrences of plant diseases, pests, weeds, and insect infestations, all contributing to failed food crop harvests (Abbas, 2022; Pickson et al., 2020; Wang & Liu, 2023; Zhao et al., 2017). Despite technological advancements, i.e. enhanced crop varieties and irrigation potentialities, global agricultural performance is subject to climate variability (Amin et al., 2015; Arhin et al., 2024; Chemura et al., 2020; Li et al., 2009; Zhao et al., 2017). Correspondingly, climate change shortens the growth cycles of food crops, leading to decreased average productivity. Over 30% of the global population is experiencing a lower food supply, increasing vulnerability to food shortages and increasing poverty rates (Sibanda & Mwamakamba, 2021). Nevertheless, countries facing food insecurity often have limited capacity to adapt to climate change (Ntiamoah et al., 2022). The most recent assessment by the State of Food Security and Nutrition in the World (2021) unveiled that 278 million people in Africa were undernourished from hunger. Extreme climate events have exposed millions of people to acute food insecurity and dwindling water reservoirs, with the most severe impacts in highly vulnerable regions (IPCC, 2022). Additionally, many regions face food insecurity in all of its forms, including availability, stability, direct market access, and competitive market pricing (Chandio et al., 2022a; Warsame et al., 2022).

Developed nations bear significant responsibility for the accumulation of GHGs due to their industrial and consumption practices, endowed with the resources to adapt and mitigate adverse climatic conditions (Janjua et al., 2014). However, the ramifications of climate variability extend globally, disproportionately impacting developing nations, particularly those reliant on subsistence rainfed agriculture and lacking sufficient financial and technological resources to address these challenges (Abbas, 2022; Ahsan et al., 2020; Ali et al., 2017; Chandio et al., 2021; Silva et al., 2023; Warsame et al., 2021). The agricultural sector serves as a cornerstone of economic growth in developing nations, contributing raw materials, employment opportunities, and export revenues (Chandio et al., 2022). In sub-Saharan Africa (SSA), where over 50% of the labour force depends on agriculture, climate change poses a substantial threat to societal livelihoods, exacerbated by rapid population growth further straining food production systems (Adhikari et al., 2015; Erdaw, 2023; Ngoma et al., 2021). Unpredictable precipitation patterns exacerbate the frequency and severity of flood and drought events, undermining the resilience of East

Africa's rainfed agriculture. Consequently, climate change threatens to destabilize food production in tropical regions like East Africa, where food shortages are already prevalent (Adhikari et al., 2015). Estimates indicate elevated cereal crop yield losses in the region due to shortened growing seasons, heightened water stress, and increased susceptibility to pests and diseases (Abdi et al., 2023b). Thus, crop diversification may become more necessary to meet the rising demand for food and support the livelihoods of low-income rural families (Li et al., 2009; Ngoma et al., 2021).

Tropical and subtropical regions face heightened vulnerability to global warming due to further temperature rises, exacerbating the strain on limited water resources and posing significant threats to agricultural crops (Ahsan et al., 2020). According to FAO (2023), climate change led to a reduction in average yields between 2000 and 2019, amounting to approximately 0.1 t/ha, representing over a 10% decline from the average observed yield during that timeframe. The persistence of severe and prolonged droughts has exacerbated food deficits in East African nations heavily reliant on limited rainfall, notably in regions such as Kenya, southern Somalia, and southern Ethiopia, where rainfall has fallen to 50% to 75% below normal levels (Nicholson, 2017). Somalia, in particular, has grappled with recurring droughts and floods since the 2010–2011 drought, exacerbating food insecurity in the country. In addition to climate variability, Somalia's agricultural sector faces challenges stemming from relatively primitive farming techniques and smallholder systems dominating the agricultural landscape. The country's primary food crops, including maize, sorghum, rice, wheat, and beans, have experienced declining productivity in recent years, highlighting the transformative impact of climate change on the productivity of Somalia's staple crops and jeopardizing its pursuit of food security. Global hunger and food instabilities are continuously rising as a consequence of the stagnant performance of the agricultural sector, hindering efforts to meet one of the core Sustainable Development Goals – Zero Hunger (Abbas, 2022).

Previous studies have reported that diverse climatic factors, such as precipitation, temperature, and environmental degradation, exert distinct impacts on crop production (Guntukula, 2020). For instance, Birthal et al. (2014) observed that an escalation in maximum temperature had a detrimental impact on crop yields, while a rise in minimum temperature was found to have a beneficial effect on the yields of certain crops. Kumar et al. (2021) contradicted this, suggesting that rising average temperatures harmed cereal crops across regions. Additionally, Li et al. (2009) warned that ongoing temperature increases could double the risk of drought-related disasters in croplands by the end of the twenty-first century. Elsewhere, Attiaoui and Boufateh (2019) discovered that cereal crops suffer more from climate change during low precipitation periods. They outlined that successful cereal growing requires persistent technical application and a conducive climate. Some studies express that precipitation and labour force have favourable impacts on crop yield (Abdi et al., 2023; Chandio et al., 2021). Inconsistencies in empirical findings persist regarding the impact of high CO_2 emissions on crop production. While Ahsan et al. (2020), Chandio et al. (2020), and Ozdemir (2022) argued for a favourable effect, Chandio et al. (2021) suggested that CO_2 emissions hampered agricultural output. On the other hand, the existing literature predominantly focuses on aggregate agricultural production, with limited attention given to crop-level analysis. Using crop production indices, studies indicated that climatic factors such as rainfall, temperature, and CO_2 had negative effects on overall cereal production in both the short-run and long-run (Ahsan et al., 2020; Chandio et al., 2020; Xiang & Solaymani, 2022). Notably, some research concentrated on the impact of climate change on major crop output. Abbas (2022) revealed that rising annual temperatures adversely affected major crop yields in Pakistan. Similarly, Gul et al. (2022) found that climatic factors, like average temperature and rainfall patterns, had a more significant influence on major food crop yields compared to non-climatic factors.

Some studies contend that climate variability influences agricultural yield differently depending on the crop. Ntiamoah et al. (2022) revealed that climate change enhanced maize and soybean yields in Ghana in the short – and long-run. Likewise, Zhang et al. (2021) indicated stable or slightly increased yields of maize, rice, and wheat under future climate conditions, thereby contributing to food security. Moreover, Ali et al. (2017) highlighted a favourable correlation between temperature and relative humidity with sugarcane yield in Pakistan. Conversely, crop-level studies noted the detrimental effects of certain climatic indicators. Chandio et al. (2023) revealed that CO_2 emissions and temperature have a negative impact on both short – and long-run maize production. Similarly, Ngoma et al. (2021) predicted decreasing crop yields due to changing precipitation and temperature, especially affecting maize in South and West Zambia. In addition, rainfall had a positive impact on rice and soybean production, while minimum temperatures negatively affected yields (Pickson et al., 2022; Satari Yuzbashkandi & Khalilian, 2020). On a global scale, sorghum and maize-growing areas were more sensitive to climatic changes than regions cultivating other crops (Li et al., 2009). The consequences of varying climatic conditions on major crop yields have been projected by several studies. Knox et al. (2012) forecast a mean crop yield decrease of 8% by the 2050s. Blanc (2012) analyzed data for 37 nations using General Circulation Models (GCM). The study projected varying changes in crop yields, including cassava decreases, maize increases, millet decreases, and sorghum decreases, depending on the specific climate change scenarios. Likewise, Adhikari et al. (2015) discovered that root crops such as cassava, sweet potato, and potato yields are less affected by climate change. The empirics attempting to determine the trends of crop yields in response to changes in climatic variables differed in crop types, regions, time periods, and analytical approaches.

Although the precise effects of climate variability on crop yields remain inconclusive and controversial, the existing line of research has failed to evaluate the crop-specific consequences of environmental alterations, thereby hindering the formulation of policy interventions aimed at offering farmers diversified crop options. Hence, more reliable estimates of climate change effects on agricultural yields at the crop level in Somalia are required. Given this backdrop, this study expands the coverage of the literature by examining the impacts of climate change factors, measured in rainfall, temperature, and GHGs, on major crop output in Somalia using annual data from 1991–2019. For agricultural development strategies to effectively mitigate and adapt to climate variability, a comprehensive understanding of the anticipated effects of climate change on agriculture at the crop level is imperative. This study diverges from the preceding studies in the following ways: Firstly, it covers the impact of climatic variables on the production of major crops by considering six main food crops for Somalia, such as maize, sorghum, rice, wheat, bananas, and beans. The majority of earlier studies used crop production indexes or single crops to analyze the effects of climate change on food security. Secondly, this study uses GHGs, which include various pollutant elements, such as CO_2, CH_4, and N_2O, that raise the average temperature, to measure the role of environmental pollution on crop output in Somalia. Most of the previous studies utilized CO_2, which is very minimal in the context of Somalia (Warsame et al., 2021; Ali Warsame & Hassan Abdi, 2023). Thirdly, the study conducts robust econometric analyses, such as the autoregressive distributed lag (ARDL) bounds testing approach and the Granger causality technique, to produce reliable results for policy actions. Fourthly, the findings are essential for policymakers to provide opportunities for innovative farming practices, technological developments, and policy interventions to play crucial roles in determining the direction of food production in the future. It also improves targeted adaptation planning and investment under the Nationally Determined Contributions (NDCs) in Somalia.

The remainder of the work is structured as follows. The second part of the paper demonstrates the climatic characteristics and trends of major crops in Somalia. The methods and data sources were provided in the third section. The fourth section indicates the results and discussion of the study. The final section provides conclusion and policy recommendations.

2. Climatic characteristics and trends of major crops in Somalia

2.1. Study area description

There are regional disparities concerning the impacts of climate change on crop cultivation. Environmental changes have been demonstrated to reduce yields for staple crops like maize and wheat in lower-altitude locations but boost yields for sugar beets, maize, and wheat in high-elevation areas (Ngoma et al., 2021). The climatic features of vital crops in Somalia differ based on the crop and the cultivation zone. A considerable amount of the country's croplands are used to cultivate and produce maize, sorghum, rice, and cowpea, which are critical for both food security and economic development. Changing weather patterns and higher GHG concentrations in the atmosphere are expected to have an influence on the growth and production of these crops. In this regard, when determining the effects of climate change on food security, it is essential to consider the variations in these crop yields. In agricultural regions, maize and sorghum are the staples selected, while rice is highly consumed in pastoral and urban regions (FEWS Net, 2023). Furthermore, access to technology, inputs, skills, and resources for mitigation and adaptation is restricted. In Somalia, the environment is suitable for growing a range of crops, such as sorghum, maize, rice, bananas, and sugarcane. In 2021, bananas, rice, and wheat were the least produced crops, with 23.53, 1.63, and 1.05 thousand tons, respectively. Temperature increases and less precipitation have led to production losses for all three cereal crops (FAO, 2022).

Given its geographical position, Somalia has a diverse climate, ranging from arid and semi-arid regions in the north and central parts to moderately humid climates in the south. Figure 1 provides the average temperature map of Somalia for the period 2011–2020. The map's colour gradient represents different temperature ranges, which can be closely correlated with the viability of various crops that can be cultivated in these thermal bands. In the cooler green-shaded areas of the north-west regions, with average temperature values between 27.61–30.88°C, conditions might be conducive to the cultivation of crops that are sensitive to heat stress, such as certain grains and vegetables. In addition, the yellow-toned regions in mainly north-earth and north-west, indicate average temperature values from 30.89–32.51°C, may represent transitional zones where heat-tolerant variants of common crops might be necessary, as the temperatures can stress plants that are not adapted to such conditions. Notably, the map highlights that inland regions, particularly central and southern Somalia, experience higher temperatures compared to coastal areas. In these warmer orange and red areas, with temperatures ranging from 32.52–35.77°C, the selection of crops becomes more critical. These areas could be cultivated with crops that are highly resistant to drought, such as sorghum, millet, or certain pulses that are adapted to arid climates. Heat stress in these zones can significantly impact flowering and fruiting stages, reduce yields, and increase irrigation demands.

2.2. Maize production

Maize stands as the cornerstone crop in Somalia, favoured for its compatibility with the country's predominant hot, dry climate and its resilience to drought conditions, playing a pivotal role in the nation's food security, especially in arid regions (Warsame et al., 2023b). Notably, Qorioley and Buale are identified as major maize cultivation zones (FEWS Net, 2023). As presented in Figure 2, trends from 1970 to 2021 reveal fluctuations in maize production and the extent of harvested land, influenced by shifts in agricultural practices, climate variability, political unrest, and economic dynamics. Initial decades saw a rise in output from 81 thousand tons in 1973 to a peak of 350 thousand tons in 1988, alongside an expansion in harvested maize area from 100 thousand hectares to 280 thousand hectares, attributable to advancements in farming techniques and technology adoption, such as the implementation of modern irrigation systems and the increased use of fertilizers (Warsame et al., 2023b). Post-1993, production and cultivated areas suffered a decline due to adverse weather events, although there was a resurgence in 1994, with production later doubling by 2002. Since then, a general decline has been observed, with maize yields falling to a significant low of 57 thousand tons in 2019, and despite recent variability, production was recorded at 75 thousand tons of maize in 2021, which still makes it one of the most popular crops in Somalia.

2.3. Sorghum production

Sorghum, a crop well-adapted to the arid and semi-arid climates of Somalia, is integral to the nation's food security due to its exceptional drought resilience and ability to prosper in low-moisture conditions. Principal regions for sorghum cultivation and consumption include Baidoa and Togwajale (FEWS Net, 2023). The historical data on sorghum production in Somalia, as illustrated in Figure 2, indicates a pattern of fluctuating yields primarily affected by environmental adversities. While sorghum production declined from 1970 to 1975, there was a significant increase in 1980, and the cultivation area expanded from 300 to over 600 thousand hectares by 1994. Initially, sorghum cultivation was managed by smallholders employing conventional methods, supporting both subsistence needs and local commerce through the 1970s and early 1980s. This swift growth is due to major investment in revitalizing agriculture with better methods in order to improve agricultural techniques and increase food security. However, the collapse of the Somali government in 1991 and the ensuing

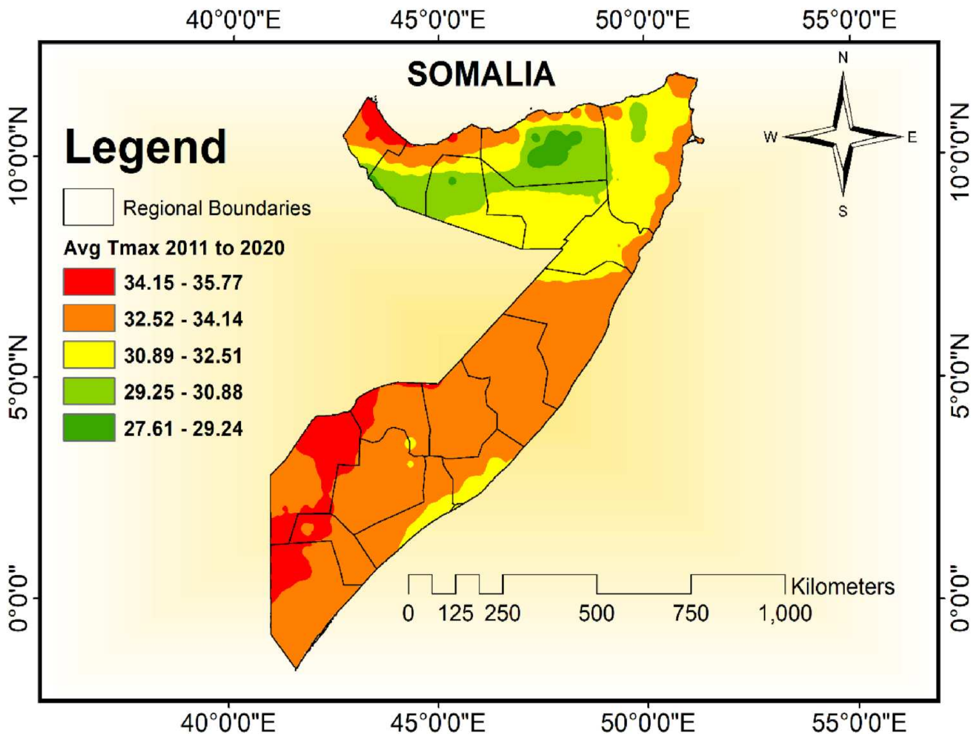

Figure 1. Average temperature map of the study area.

civil strife severely disrupted agricultural activities. The ensuing conflict led to farmer displacement and field abandonment, which, coupled with severe droughts and famine, culminated in a historic low yield of 48 thousand tons in 2011 (Abdi et al., 2023a). Although there was a recovery in the following years, sorghum production has faced persistent challenges, such as limited modern agricultural techniques, inadequate infrastructure, frequent extreme weather events, and ongoing political instability. By 2021, sorghum production had steadied at 100 thousand tons, positioning it as Somalia's second-most-produced crop despite the ongoing adversities.

2.4. Rice production

Rice, a primary dietary staple for over half the global population and the world's third most produced grain, faces yield challenges due to climatic fluctuations affecting its growth stages (Abbas & Mayo, 2021; Pickson et al., 2022). In Somalia, rice is often grown in southern areas, such as the Shabelle and Juba River basins, where the climate is more humid. Although limited in amount, local farmers grew rice mainly for domestic consumption in areas with access to irrigation or areas near rivers, as the crop requires an immense amount of water. As depicted in Figure 2, the trends in rice production in Somalia from 1970 to 2021 have been inconsistent. Starting with yields under 2,000 tons in the early 1970s, there was an upsurge to 19 thousand tons by 1982, with the harvest area expanding to 9,800 hectares by 1979. Since then, rice production and harvested land have experienced erratic fluctuations, with a stabilization of around 2,000 tons annually during 1994–2000. A notable surge to 18 thousand tons occurred in 2004, but a general decline followed, reaching the lowest level in 2014. Between 2015 and 2021, rice yields have been comparatively low and static, especially against staples like sorghum and maize. The cultivated area for rice has also seen minimal growth, ultimately contracting to below 2,000 hectares in recent years.

2.5. Wheat production

Wheat is not a traditional staple crop in Somalia, and its output has traditionally been limited. The cultivation of

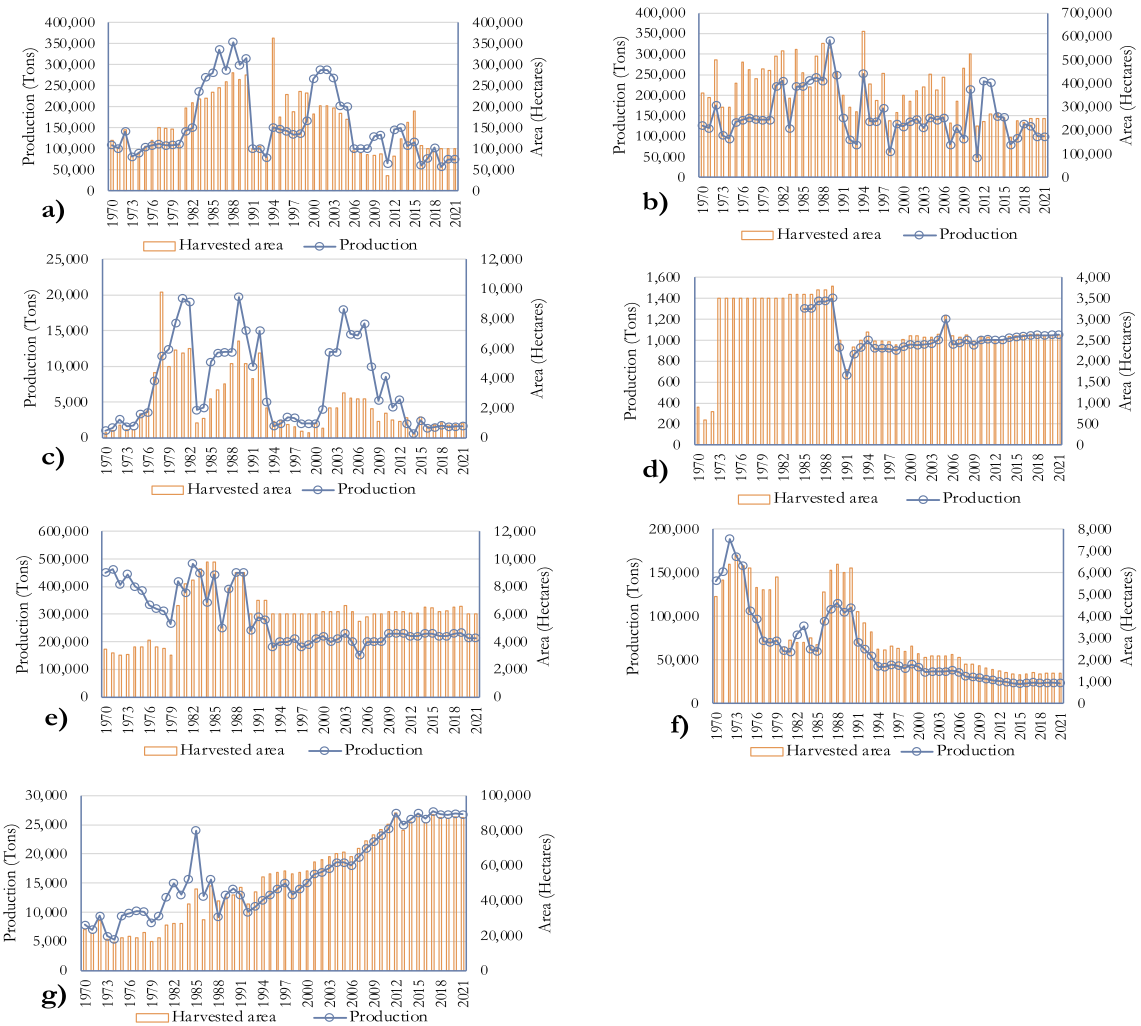

Figure 2. Trend of major crops production and harvested areas.
Notes: (a) Maize (b) Sorghum (c) Rice (d) Wheat (e) Sugarcane (f) Banana (g) Beans. Data source: FAO (2022).

wheat in Somalia was small-scale and focused on specific regions where the temperature and soil conditions were favourable for its development. The country's climatic conditions and the minimal agricultural development activities contributed to the limited expansion of wheat production. To meet domestic wheat consumption demands, Somalia continues to be dependent on imports. Data from Figure 2 indicate a static trend in wheat production and harvested area from 1985 to 2021. Initially, production marginally rose from 1,300 tons in 1985–1,400 tons in 1989, but then dropped to 660 tons by 1992. Meanwhile, the harvested area experienced a significant increase from 600 hectares in 1971 to a peak of 3,500 hectares in 1973, stabilizing at 1,800 hectares by 1989. A subsequent increment to over 2,500 hectares was observed in 1994, a figure that has persisted for the last quarter century. Production modestly recovered to about 1,000 tons and maintained stability until 2004. It underwent a minor increase to 1,200 tons in 2005, followed by a decrease to 960 tons in 2006. From 2006 onwards, wheat production has remained consistent. The increasing demand for food, coupled with unchanging wheat production, poses a risk of intensifying Somalia's food security challenges.

2.6. Sugarcane production

Sugarcane cultivation is predominantly undertaken in regions characterized by tropical or subtropical climates, where temperatures are warm year-round. This crop necessitates a copious supply of water and is typically cultivated in areas equipped with comprehensive irrigation systems to meet its substantial hydration requirements. Over the years, sugarcane production in Somalia has witnessed oscillations, as shown in Figure 2. It is one of the most widely grown crops in the nation, with 450 thousand tons produced in 1970. A series of declines in sugarcane yield demonstrated a sluggish trajectory, resulting in a loss of more than a third in output in 1979. This is due to the fact that smallholder family farms dominate the country's sugarcane industry. Sugarcane output quickly rebounded, attaining an unprecedented level of almost half a million tons in 1982. Furthermore, the harvested area for sugarcane initially remained modest but expanded from 6,600 hectares in 1979–9,800 hectares in 1986. A period of instability followed, with a notable drop to 180 thousand tons in 2005. However, over the past three decades, production has levelled out to an average of 200 thousand tons. Similarly, after a decade of variations, the harvested area has stabilized at around 6,000 hectares for more than twenty years. By 2021, Somalia's sugarcane production stood at 213 thousand tons, making it the country's most abundant crop.

2.7. Banana production

Bananas in Somalia are cultivated particularly in the favourable climatic conditions of the Lower and Middle Shabelle regions. The crop needs a tropical or subtropical environment with plenty of rainfall and humidity. Figure 2 chronicles the trajectory of banana production and the extent of the harvested area from 1970 to 2021. Initially, production was robust, peaking at 168 thousand tons in 1973, reflecting the crop's export-centric cultivation with an expansion from 4,900 hectares in 1970–6,300 hectares by 1974. During the pre-1980s, Somalia's economy benefited significantly from banana exports. However, the sector witnessed a drastic downturn, with output descending to 59 thousand tons by 1981. Although there was a brief recovery in subsequent years, production has been on a general decline, dwindling from 42 thousand tons in 1995 to just 23.5 thousand tons in 2021. Contributing to this decline were the instability and civil unrest that led to the abandonment of many banana farms. Traditional, predominantly rain-fed agricultural methods further exacerbated the crop's vulnerability to the climate. The harvested area saw a decrease to 2,700 hectares in 1986, followed by a slight increase to 6,400 hectares in 1989, and then a gradual reduction over the following thirty years. Despite these adversities, smallholder farmers persist in growing bananas primarily for local markets, while large-scale commercial production and exportation have significantly diminished. By 2021, Somalia's banana production was recorded at 23.5 thousand tons.

2.8. Beans production

In Somalia, beans serve as a versatile and resilient crop, capable of being cultivated in a wide range of climatic conditions, from arid to humid, making them a key component of the nation's food security strategy. They are integral to the diet of Somali households and are predominantly grown in regions such as El Dher and Merka (FEWS Net, 2023). The production trend of beans, as shown in Figure 2, has been generally upward from 1970 to 2021, with an initial output of around 10 thousand tons. In 1985, production peaked at 24 thousand tons but subsequently declined to 9,200 tons in 1988. Over the past few decades, beans have maintained their status as a staple crop, with production steadily increasing from 10 thousand tons in 1992 to over 25 thousand tons in 2021. Despite this growth, production still falls short of meeting the country's nutritional needs, leading to a reliance on imports. Beans also rank as one of the crops with the largest harvested area in Somalia, trailing only maize and sorghum. Starting from a lower base, the harvested area for beans expanded significantly, from 27 thousand hectares in 1984–90 thousand hectares in 2012. However, bean cultivation has not been without its challenges, including recurrent droughts and variable weather conditions that have affected production. In 2021, the country's bean production reached 26 thousand tons, reflecting both the crop's importance to the agricultural sector and the ongoing challenges it faces.

3. Data and methodology

3.1. Climate and crop data

The study adopted annual time series data from 1991 to 2019 to examine the ramifications of climate change on selected major crops in Somalia. Climate effects became prevalent in the country, undermining agricultural yields, on which the nation relies for food security and economic prosperity. Consequently, the

Table 1. Variables, code, measurement unit, and sources.

Variable	Major Crops	Code	Measurement Unit	Source
Crop production (CP)	Maize production	MP	Production quantity (tons)	FAO
	Sorghum production	SOP	Production quantity (tons)	FAO
	Rice production	RP	Production quantity (tons)	FAO
	Wheat production	WP	Production quantity (tons)	FAO
	Sugarcane production	SCP	Production quantity (tons)	FAO
	Banana production	BP	Production quantity (tons)	FAO
	Beans production	BEP	Production quantity (tons)	FAO
Crop harvested area (CHA)	Maize harvested area	MHA	Area harvested (hectares)	FAO
	Sorghum harvested area	SOHA	Area harvested (hectares)	FAO
	Rice harvested area	RHA	Area harvested (hectares)	FAO
	Wheat harvested area	WHA	Area harvested (hectares)	FAO
	Sugarcane harvested area	SCHA	Area harvested (hectares)	FAO
	Banana harvested area	BHA	Area harvested (hectares)	FAO
	Beans harvested area	BEHA	Area harvested (hectares)	FAO
Precipitation level		AP	Annual average rainfall mm	CCKP
Temperature variability		TC	Average annual temperature change (°C)	FAO
Greenhouse gas emissions		GHGs	Total GHGs (kt of CO_2 equivalent)	WB
Agricultural labour		AL	Rural population (% of total population)	WDI

study applies the output of a variety of agricultural products, such as maize, sorghum, rice, wheat, sugarcane, bananas, and beans, as dependent variables. Average rainfall, temperature, and GHG emissions are considered climatic variables that are affecting agricultural output (Chandio et al., 2022; Rehman et al., 2022). In order to avoid model misspecification and variable omissions, the study considered non-climatic aspects, such as crop-harvested areas and agricultural labour, that have an impact on the production of major crops (Pickson et al., 2022). The data used in this study were gathered from the Food and Agriculture Organization (FAO), the World Bank (WB), and the Climate Change Knowledge Portal (CCKP). The duration of the analyzed data was established with regard to the availability of data across each variable. The variables, code, measurements, and data sources are shown in Table 1.

3.2. Econometric model specification

This study ensues the preceding empirical investigations of Chandio et al. (2020), Janjua et al. (2014), Warsame et al. (2021), Kumar et al. (2021), and Gul et al. (2022), who contained average precipitation, temperature, environmental degradation, crop harvested area, and agricultural labour in their studies. Unlike the previous studies, which used carbon emissions and cultivated land area in their estimations, we considered a broader context of environmental degradation, GHGs, and crop harvested area instead of land under cultivation. As a consequence, we adopted the following function to study the impacts of climatic and non-climatic variables on major crop output in Somalia:

$$CP = f(AP, TC, GHGs, CHA, AL) \quad (1)$$

1)where CP represents various crop production models, i.e. maize, sorghum, rice, wheat, sugarcane, bananas, and beans, which are the dependent variables; AP signals average precipitation levels; TC symbolizes temperature variability; GHGs measure greenhouse gas emissions; CHA is for crop harvested area; and AL signifies agricultural labour. The entire variables of the study in Equation (1) were converted into natural logarithms to circumvent the incidence of heteroskedasticity issues and interpret our outcomes in percentage form. The generalized econometric model is presented as follows:

$$lnCP_t = \beta_0 + \beta_1 lnAP_t + \beta_2 lnTC_t + \beta_3 lnGHGs_t + \beta_4 lnCHA_t + \beta_5 lnAL_t + \varepsilon_t \quad (2)$$

The ln stands for the natural logarithm, ε_t represents the white noise error term, and β_0 indicates the intercept. Crop output is very sensitive to climatic variations caused by changes in precipitation patterns and a rise in yearly temperature, while agricultural inputs like harvested area and labour improve crop yield. Hence, β_1, β_4, and β_5 are the coefficients of average precipitation, crop harvested area, and agricultural labour, respectively, which are anticipated to have a positive impact on the production of crops. However, β_2 and β_3 are the coefficients of temperature changes and GHGs, which are predicted to have a negative effect on the performance of major agricultural crops.

As suggested by Pesaran et al. (2001), the ARDL bound test was applied to inspect the long-run and short-run relationships among the factors presented in equation (2). The bound test approach surpasses other traditional methods of cointegration, i.e. Engle and Granger (1991) as well as Johansen and Juselius (1990) cointegration methods, because it predicts variables irrespective of whether they are stationary at level *I(0)*, at first difference *I(1)*, or a combined integration. Additionally, it is genuine and adequate to estimate the cointegration relationship of a relatively small number of samples. It also determines both long-run and short-run coefficients concurrently. However, it is not appropriate for higher orders of integration, i.e. the second difference, *I(2)*. Using Equation (2), the long-run and short-run equation of the ARDL bound test is constructed as follows:

$$\begin{aligned}\Delta lnCP_t = \Omega_0 &+ \sum_{i=1}^{p}\varphi_1\Delta lnCP_{t-i} + \sum_{i=1}^{q}\varphi_2\Delta lnAP_{t-i} \\ &+ \sum_{i=1}^{q}\varphi_3\Delta lnTC_{t-i} + \sum_{i=1}^{q}\varphi_4\Delta lnGHGs_{t-i} \\ &+ \sum_{i=1}^{q}\varphi_5\Delta lnCHA_{t-i} + \sum_{i=1}^{q}\varphi_6\Delta lnAL_{t-i} \\ &+ \psi_1 lnCP_{t-1} + \psi_2 lnAP_{t-1} + \psi_3 lnTC_{t-1} \\ &+ \psi_4 lnGHGs_{t-1} + \psi_5 lnCHA_{t-1} + \psi_6 lnAL_{t-1} + \varepsilon_t \end{aligned} \tag{3}$$

whereas Ω_0 is the constant, $\varphi_1 - \varphi_6$ represents the coefficients of the short-tun, $\psi_1 - \psi_6$symbolizes the coefficients of the long-run variables, p and q signifies optimal lag lengths of the explained variable and the regressors, the symbol Δ stands for short-run parameters, and i represents the lagged values. Initially, we embrace the ordinary least squares (OLS) regression approach to analyze Equation (3) in order to discover the long-run cointegration between the fundamental variables. In this undertaking, the bounds test F-statistic is implemented to compare the null hypothesis of no long-run cointegration association among climatic, non-climatic, and major crop yield variables in Somalia (H_0:$\psi_1 = \psi_2 = \psi_3 = \psi_4 = \psi_5 = \psi_6 = \psi_7 = 0$) against the alternative hypothesis of long-run cointegration ties between the underlying variables (H_1:$\psi_1 \neq \psi_2 \neq \psi_3 \neq \psi_4 \neq \psi_5 \neq \psi_6 \neq \psi_7 = 0$). On the basis of Pesaran et al. (2001), the F-bound test is compared with the bound critical values to figure out if there is cointegration. The null hypothesis of no cointegration will be rejected if the estimated F-bound test result surpasses the upper bound critical value, which suggests a long-run connection. Nevertheless, the null hypothesis cannot be rejected if the estimated value of the F-bound test is smaller than the crucial value, which proves the absence of a long-run association. The result is still inconclusive if the predicted F-bound value is between the upper and lower critical levels.

The study further utilized the error correction model (ECM) for figuring out the short-run relationships between average precipitation, temperature change, greenhouse gas emissions, agricultural labour, major crop harvested areas, and production. In addition, η represents the coefficient of the error correction term (ECT). Equation (4) can be expressed in terms of error correction specification as follows:

$$\begin{aligned}\Delta lnCP_t = \varphi_0 &+ \sum_{i=1}^{p}\varphi_1\Delta lnCP_{t-i} + \sum_{i=1}^{q}\varphi_2\Delta lnAP_{t-i} \\ &+ \sum_{i=1}^{q}\varphi_3\Delta lnTC_{t-i} + \sum_{i=1}^{q}\varphi_4\Delta lnGHGs_{t-i} \\ &+ \sum_{i=1}^{q}\varphi_5\Delta lnCHA_{t-i} + \sum_{i=1}^{q}\varphi_6\Delta lnAL_{t-i} \\ &+ \eta ECT_{t-1} + \varepsilon_t \end{aligned} \tag{4}$$

4. Empirical results and discussion

4.1. Descriptive statistics

The descriptive statistics summarize the most significant features of the series, such as the mean, minimum, maximum, volatility, skewness, and normality. As displayed in Table 2, the sorghum harvested area exhibited the highest average and maximum values of 12.67 and 13.34, respectively. However, the mean value of sugarcane production was the highest at 12.27 compared to other crops. The average value of climate change variables such as rainfall, temperature, and GHGs was 5.62, − 0.12, and 10.12, respectively. In the same vein, temperature variation displayed the lowest maximum and minimum values of 0.56 and − 1.20, respectively. The sugarcane harvested area has the lowest volatility of 0.05, whereas rice production has the highest value of 0.94. This indicates that the standard deviation of all series is less than one, which indicates that the dispersion of the data is very small and that heterogeneity could be less of an issue in the study. Table 2 also demonstrates that the majority of the variables are negatively skewed except rainfall, the production

Table 2. Descriptive statistics and correlation matrix.

Variable	Major crop	Mean	Maximum	Minimum	Std. Dev.	Skewness	Kurtosis	Jarque-Bera	Prob.	Obs.
lnCP	lnMP	11.764	12.569	10.951	0.445	0.166	2.493	0.443	0.801	29
	lnSOP	11.743	12.438	10.789	0.379	−0.382	3.249	0.778	0.678	29
	lnRP	8.333	9.798	6.397	0.946	0.055	1.844	1.63	0.443	29
	lnWP	6.875	7.09	6.492	0.096	−1.877	10.296	81.341	0.000	29
	lnSCP	12.272	12.578	11.918	0.126	−0.108	4.683	3.477	0.176	29
	lnBP	10.442	11.156	10.014	0.311	0.409	2.452	1.17	0.557	29
	lnBEP	9.819	10.215	9.21	0.309	−0.229	1.831	1.906	0.386	29
lnAP		5.624	5.854	5.439	0.102	0.391	3.12	0.757	0.685	29
lnTC		−0.122	0.561	−1.201	0.45	−0.493	2.588	1.378	0.502	29
lnGHGs		10.121	10.208	9.889	0.066	−2.045	7.223	41.757	0.000	29
lnCHA	lnMHA	11.796	12.801	10.502	0.484	−0.296	3.074	0.429	0.807	29
	lnSOHA	12.666	13.339	12.039	0.297	0.228	2.614	0.432	0.806	29
	lnRHA	7.158	8.643	5.704	0.685	−0.044	2.845	0.039	0.981	29
	lnWHA	7.84	8.039	7.496	0.081	−2.232	13.204	149.886	0.000	29
	lnSCHA	8.732	8.854	8.613	0.051	0.55	3.892	2.423	0.298	29
	lnBHA	7.609	8.343	7.178	0.314	0.43	2.511	1.182	0.554	29
	lnBEHA	11.111	11.408	10.545	0.231	−0.479	2.477	1.437	0.487	29
lnAL		4.145	4.248	3.997	0.081	−0.467	1.792	2.817	0.244	29

of maize, rice, and banana, and the harvested areas of sorghum, sugarcane, and banana, which are positively skewed. The *p*-values of the Jarque-Bera statistic indicate that wheat production, greenhouse gases, and wheat harvested area are normally and identically distributed, while the rest of the variables are not.

4.2. Unit root test

It is very common for time-series data to incorporate trends that could lead to spurious estimates. Therefore, to deal with the non-stationarity issues that usually arise in time-series data, we used various unit root tests, such as the Augmented Dickey-Fuller (ADF) and Philips Perron (PP) tests. In contrast to the alternative hypothesis (H_1) of both tests that the series is stationary, the null hypothesis (H_0) states that the series has a unit root. As presented in Table 3, the results of the ADF and PP unit root tests exhibit that the series is stationary at various orders of integration. The outcomes of both tests reveal that there is a unit root for most of the series at I(0). However, all the variables developed into stationary after I(1). Since the outcomes demonstrate that the stationarity of the variables exhibits various orders of integration, i.e. I(0) and I(1), this reinforces the appropriateness of the ARDL approach and proposes that we can advance to the cointegration analysis of the study.

4.3. Cointegration test

Upon validation that the variables under consideration satisfied the unit root properties, we investigated co-integration between the climate change variables, non-climatic factors, and major crop production. The F-bound test has been used as presented in Table 4. The scrutiny method is based on the arrangement of critical values by Narayan (2005). The results of the F-bound test statistics indicate that the maize crop yield falls below the lower bound critical value (3.082) at a 5% significance level. This indicates that we fail to reject the null hypothesis of no cointegration between the variables under consideration and maize output. In addition, the F-bound test statistics of sorghum, rice, sugarcane, banana, and bean production fall above the upper bound critical values at a 5% significance level. This demonstrates that climatic and non-climatic factors have a long-run cointegration linkage with these variables. However, the F-bound test outcome of the wheat production model displayed that it fell between the upper and lower bound critical values (4.293) at the 5% significance level. This implies that the cointegration relationship could be inconclusive. This confirms that we could proceed with the estimation of the long-run and short-run relationships between the variables.

4.4. Long-run and short-run estimates

The estimates of the long-run coefficients are determined after ascertaining the cointegration relationship between the variables. The long-run results of the various models of crop output have been presented in Table 5. The outcomes reveal that precipitation increases have a constructive role in

Table 3. Unit Root Tests.

	ADF Test				PP Test			
	Level		First difference		Level		First difference	
Variables	Constant	Constant with trend	Constant	Constant with trend	Constant	Constant with trend	Constant	Constant with trend
lnMP	−1.924	−2.432	−6.363***	−6.502***	−1.91	−2.251	−6.486***	−7.133***
lnSOP	−6.686***	−6.556***	−9.968***	−9.766***	−10.873***	−10.604***	−27.843***	−35.338***
lnRP	−3.177**	−3.128	−5.539***	−5.429***	−1.863	−1.925	−5.539***	−5.430***
lnWP	−5.983***	−6.947***	−5.405***	−5.207***	−5.790***	−7.103***	−16.072***	−17.685***
lnSCP	−4.034***	−4.283**	−6.873***	−6.651***	−4.024***	−4.917***	−6.846***	−7.629***
lnBP	−2.422	−2.515	−3.314**	−4.154**	−2.378	−3.269*	−4.733***	−5.014***
lnBEP	−0.596	−4.012**	−8.277***	−8.431***	−0.335	−4.159**	−8.417***	−10.248***
lnAP	−2.860*	−5.719***	−9.759***	−6.494***	−4.340***	−5.736***	−23.790***	−23.692***
lnTC	−0.971	−4.980***	−4.663***	−4.689***	−3.065**	−15.031***	−28.858***	−38.734***
lnGHG	−8.807***	−6.868***	−5.451***	−4.725***	−2.49	−1.461	−5.328***	−6.223***
lnMHA	−2.649*	−3.234*	−7.404***	−7.335***	−2.549	−3.162	−7.402***	−7.349***
lnSOHA	−3.574**	−4.356***	−5.105***	−4.062**	−3.577**	−4.291**	−16.538***	−19.942***
lnRHA	−3.954***	−3.872**	−8.176***	−8.212***	−2.907*	−2.849	−7.854***	−7.877***
lnWHA	−7.218***	−6.786***	−5.184***	−4.986***	−7.255***	−6.792***	−15.302***	−18.695***
lnSCHA	−1.868	−3.006	−4.215***	−4.198**	−3.413**	−3.610**	−5.228***	−5.896***
lnBHA	−0.631	−2.096	−1.683	−1.668	−2.506	−3.312*	−4.625***	−4.803***
lnBEHA	−1.126	−3.281*	−7.817***	−8.402***	−0.96	−3.390*	−7.522***	−8.402***
lnAL	0.75	−1.82	−4.874***	−5.036***	1.517	−1.692	−4.873***	−5.034***

Note: ***, **, * denote significance at 1%, 5% and 10%, respectively.

Table 4. F-bounds test cointegration results.

Model	F-statistic	Signif.	Bounds test critical values (k = 5) I(0)	I(1)	Decision
lnMaize = *f*(lnAP, lnTC, lnGHG, lnMHA, lnAL)	3.082	5%	3.125	4.608	No cointegration
		10%	2.578	3.858	
lnBP = *f*(lnAP, lnTC, lnGHG, lnBHA, lnAL)	5.581	5%	3.125	4.608	Cointegration
		10%	2.578	3.858	
lnRP = *f*(lnAP, lnTC, lnGHG, lnRHA, lnAL)	8.301	5%	3.125	4.608	Cointegration
		10%	2.578	3.858	
lnWP = *f*(lnAP, lnTC, lnGHG, lnWHA, lnAL)	4.293	5%	3.125	4.608	Inconclusive
		10%	2.578	3.858	
lnSCP = *f*(lnAP, lnTC, lnGHG, lnSCHA, lnAL)	5.643	5%	3.125	4.608	Cointegration
		10%	2.578	3.858	
lnSOP = *f*(lnAP, lnTC, lnGHG, lnSOHA, lnAL)	8.360	5%	3.125	4.608	Cointegration
		10%	2.578	3.858	
lnBEP = *f*(lnAP, lnTC, lnGHG, lnBEHA, lnAL)	15.291	5%	3.125	4.608	Cointegration
		10%	2.578	3.858	

Note: The F-bounds test critical values are from Narayan (2005) based on the 5% significance level.

sorghum, sugarcane, and banana yields, with an average increase of 2.41%, 0.16%, and 0.10%, respectively. However, the effects of rainfall on the production of beans were negative, even though we found that its effects on rice production were statistically insignificant. Additionally, the long-run findings reveal that temperature increases play a devastating role in major crop production. Interpretively, temperature variations reduce the production of sorghum, rice, banana, and bean yields by 1.30%, 0.58%, 0.10%, and 0.04%, respectively, if they are increased by 1 percentage point. On the contrary, the findings display that temperature change enhances the production of sugarcane by 0.045%. Another striking result from the study indicates that GHGs enhance the production of all selected major crops in the long-run except sugarcane, which was found to be statistically insignificant. This suggests that a percentage rise in GHGs stimulates the yield of sorghum, rice, bananas, and beans by about 1.74%, 2.28%, 0.16%, and 0.20%, respectively. Moreover, the entire set of regressors is statistically significant to explain

Table 5. Long-Run Coefficient Estimates.

Variable	lnSOP	lnRP	lnSCP	lnBP	lnBEP
Constant	−14.347	−20.522	8.549***	−0.018	−3.822***
	(−1.704)	(−1.527)	(4.449)	(−0.030)	(−4.415)
lnAP	2.416***	−1.178	0.167**	0.104**	−0.124***
	(3.409)	(−1.446)	(2.482)	(3.115)	(−5.066)
lnTC	−1.307***	−0.588**	0.045**	−0.102***	−0.042***
	(−4.382)	(−2.349)	(3.256)	(−6.639)	(−2.604)
lnGHGs	1.749**	2.283*	0.170	0.160***	0.209***
	(2.367)	(1.981)	(0.920)	(3.844)	(4.041)
lnCHA*	1.396***	0.707***	−0.192	0.499***	0.756***
	(4.342)	(9.227)	(−0.546)	(9.665)	(14.261)
lnAL	−7.328***	0.800	−0.277**	0.220**	−0.214**
	(−4.366)	(0.730)	(−3.444)	(3.130)	(−2.505)

Note: The crop harvested area (CHA) represents the harvested areas of sorghum, rice, sugarcane, banana, and beans.

the constructive role of crop harvested area in stimulating major crop output in the long run, except for sugarcane, which was found to be statistically insignificant. This proposes that a percentage upsurge in the harvested areas of sorghum, rice, bananas, and beans contributes to the yield of these crops by about 1.39%, 0.70%, 0.49%, and 0.75%, respectively. Furthermore, agricultural labour has long-run positive effects on the yield of bananas only, with a 1% rise in agricultural labour leading to a 0.22% increase in banana production. However, the long-run findings indicate agricultural labour reduces the production of major crops, i.e. sorghum, sugarcane, and beans, with a percentage increase causing a decline of about 7.32%, 0.27%, and 0.21%, respectively.

On the other hand, the short-run findings have been presented in Table 6. The results disclose that a 1 percent increase in the previous year's sorghum, banana, and bean output leads to a significant decrease in their current year's production, on average, by 0.37%, 1.26%, and 0.42%, respectively. However, the previous lags in sugarcane yield enhance the current year's output by 0.60% in the short-run. Moreover, rainfall has a favourable influence on bean production in the short-run, with a percentage increase boosting the yield by 0.12%. Similarly, the previous year's rainfall stimulates the current year's harvest in rice and sugarcane by 1.67% and 0.19%, respectively. In contrast, both the current and previous lags in rainfall reveal that an increase in the amount of precipitation decreases the harvest of bananas and sorghum. The short-run precipitation also decrease the production of sugarcane by 0.24%.

Furthermore, the short-run results suggest that temperatures do not influence the output of sugarcane and bananas since the probability values of the coefficients are statistically insignificant. The yield of rice and sorghum is positively related to temperature increases in the short-run, although temperature variations reduce bean production by 0.04%. Moreover, the findings specified that both the current and previous lags of GHGs enhance the production of sorghum, beans, sugarcane, and bananas. Interpretively, a percentage increase in the current lag of GHGs augments the harvest of sorghum and beans by about 7.56% and 0.93% in the short-run. Nevertheless, the outcomes reveal that the previous lags in GHGs hamper rice, sugarcane, and bean production. Moreover, the harvested areas for the entire crops were found to positively affect the selected crop production. A percentage increase in the harvested area of sorghum, rice, sugarcane, and bean production improves the yield of these crops by 1.05%, 0.73%, 2.08%, and 0.82%, respectively. Similarly, the previous year's sugarcane, banana, and bean harvest areas positively influenced their current year's production. However, the previous year's sorghum harvested areas negatively influence the yield of sorghum in the short-run. The results also indicate that the previous year's agricultural labour positively raise the output of bananas in the short-run. Interpretively, a 1% increase in agricultural labour will increase banana yield by 1.53% in the short-run. The previous lags in agricultural labour were also found to adversely influence the harvest of sugarcane and sorghum in the short-run. As disclosed in Table 6, the error correction term (ECT), which shows the rate at which any short-run shock in the factors under investigation reverts to long-run equilibrium, is negative and statistically significant for all models in the study. The ECT coefficients for sorghum, rice, sugarcane, banana, and bean production are − 0.75, − 0.41, − 0.77, − 0.31, and − 0.09, respectively. This

Table 6. Short-Run Coefficient Estimates.

Variable	lnSOP	lnRP	lnSCP	lnBP	lnBEP
Constant	5.333*** (6.500)	1.575** (2.669)	2.968** (2.863)	1.110** (2.441)	0.455** (2.106)
$\Delta lnSOP_{t-1}$	−0.379*** (−3.799)				
$\Delta lnRP_{t-1}$		0.151 (1.214)			
$\Delta lnSCP_{t-1}$			0.608** (2.328)		
$\Delta lnSCP_{t-2}$			0.16 (1.189)		
$\Delta lnBP_{t-1}$				−1.263** (−2.369)	
$\Delta lnBEP_{t-1}$					−0.054 (−0.566)
$\Delta lnBEP_{t-2}$					−0.424*** (−3.221)
$\Delta lnAP$	−0.935*** (−3.179)		−0.245** (−2.441)	−0.199* (−1.964)	0.124*** (3.273)
$\Delta lnAP_{t-1}$	−1.915*** (−5.777)	1.670** (2.249)	−0.162 (−1.305)	−0.269** (−2.818)	
$\Delta lnAP_{t-2}$		1.226 (1.670)	0.194* (1.979)		
$\Delta lnTC$		0.479* (1.805)	0.0341 (1.722)		
$\Delta lnTC_{t-1}$	0.825*** (5.037)	0.869*** (3.373)		−0.008 (−0.201)	
$\Delta lnTC_{t-2}$	0.253** (2.142)			−0.041 (−1.039)	−0.045*** (−3.463)
$\Delta lnGHGS$	7.566*** (5.631)	6.122 (1.263)	−2.463** (−2.987)		0.933** (2.410)
$\Delta lnGHGS_{t-1}$		−11.579** (−2.680)	4.672*** (4.414)	0.167 (0.364)	−1.189*** (−3.881)
$\Delta lnGHGS_{t-2}$			−1.641*** (−3.909)	1.184*** (3.531)	
$\Delta lnCHA$	1.055*** (8.535)	0.731*** (5.781)	2.081*** (8.523)		0.820*** (6.843)
$\Delta lnCHA_{t-1}$	−0.165*** (−0.998)			1.620*** (3.027)	
$\Delta lnCHA_{t-2}$	−0.736*** (−6.220)	0.183 (1.437)	0.889* (2.163)		0.634*** (4.714)
$\Delta lnAL$					
$\Delta lnAL_{t-1}$		−8.656 (−1.436)		1.535* (1.870)	−0.574 (−1.279)
$\Delta lnAL_{t-2}$	−17.552*** (−6.670)		−1.475* (−2.006)		
ECT_{t-1}	−0.753*** (−6.696)	−0.418** (−2.877)	−0.775** (−2.865)	−0.318** (−2.463)	−0.093** (−2.044)

implies that any deviation from equilibrium in the production of major crops in Somalia is corrected by 75% (sorghum), 41% (rice), 77% (sugarcane), 31% (bananas), and 9% (bean) by the relevant explanatory factors annually.

In comparison to prior studies, the finding that precipitation has a productive influence on the output of various crops is comparable to Kumar et al. (2021), who confirmed the favourable influence of adequate rainfall on cereal crops. Some studies assert that changes in precipitation will likely result in a steady drop in crop output (Attiaoui & Boufateh, 2019; Ngoma et al., 2021). The literature acceded that intense rainfall is a significant threat to farm yields, which has a high impact on livelihood in developing countries where the population depends on rainfed agriculture (Ozdemir, 2022; Xiang & Solaymani, 2022). The crop level studies are comparable to our mixed findings about the precipitation effects on crop production. Satari Yuzbashkandi and Khalilian (2020) perceived that rainfall exhibited a noteworthy positive impact on soybean yield. In the same vein, Abbas and Mayo (2021) and Pickson et al. (2022) reach the same conclusion that rainfall has a positive impact on rice plants. For wheat crop yield, Abbas (2022) noticed that precipitation had a detrimental effect, while Shayanmehr et al. (2020) discovered that rainfall positively affects irrigated and rainfed wheat. Due to a lack of major irrigation infrastructure and the semi-arid to arid climate, Somalia's agricultural practices depend heavily on natural rainfall for irrigation and moisture to sustain crop development. Precipitation in Somalia is irregular and unpredictable, posing problems for popular rainfed crops such as sorghum, maize, millet, beans, and vegetables.

In addition, the evidence from various regions validates the result that temperature hampers crop output, although its effect varies with crop type. For instance, Abbas (2022) in Pakistan, Birthal et al. (2014) in India, and Tetteh et al. (2022) in Ghana supported that temperature had a detrimental impact on crop yields. Also, panel studies across various regions in the developing world emphasized that changes in temperature will likely result in a steady drop in crop yield (Abdi et al., 2023b; Kumar et al., 2021; Ozdemir, 2022). High temperatures may worsen water shortage issues by accelerating heat stress in plants and water loss from the soil. Since plants lack the essential water for their physiological requirements, this has resulted in drought conditions in Somalia, aggravating crop growth. Furthermore, increased temperatures shifted agricultural growth seasons, leading crops to be planted earlier or later than typical. At the crop level, Warsame et al. (2022) confirmed that temperature changes were negatively correlated with sorghum yield in Somalia, while Ali et al. (2017) observed a favourable correlation between temperature and sugarcane yield in Pakistan. Besides, Ntiamoah et al. (2022) revealed that climate factors enhance maize and soybean yields in Ghana in both the short – and long-run. Warmer temperatures also cause pest and disease ranges to expand. Somalia, like many other East African nations, has recently witnessed locust outbreaks that have resulted in severe crop loss, resulting in food shortages and economic hardships for impacted areas.

Moreover, the constructive role of GHGs on major crop output in our study endorses Ahsan et al. (2020), who reveal optimal levels of CO_2 emissions can have a favourable influence on cereal crop output. Moreover, Ozdemir (2022) found that CO_2 emissions are positively associated with agricultural productivity in the short-run, while they turn negative in the long-run. However, the beneficial impacts of higher GHGs on crop growth are anticipated to be overshadowed by the overall negative consequences of climate change on agriculture, ecosystems, and societies. Chandio et al. (2023), who found that long-run environmental deterioration harms crop productivity in Nepal. Furthermore, the negative contribution of agricultural labour to various crops is supported by Ahsan et al. (2020) and Warsame et al. (2023). Because access to formal education tends to be limited in rural and distant places, numerous farmers in Somalia may have lower levels of skills. The literature asserts that, due to a lack of adequate training and tools, the labour force is negatively related to agricultural production. However, it contradicts Abdi et al. (2023b) and Chandio et al. (2021), who revealed that agricultural labour has a favourable impact on output. In excess, the finding that crop harvested area increases the yield of the selected crops embraces the prior findings of Ahsan et al. (2020), Pickson et al. (2022), and Ahsan et al. (2020). Accordingly, the available arable land and suitable conditions for cultivation improve the total harvested crop area. In addition, Warsame et al. (2022) reinforce our finding that sorghum-cultivated land has a long-run positive effect on sorghum yield.

The outcomes of our investigations of the climate change resilience of major crops in Somalia imply that the drought-resistant nature of maize and sorghum has been compromised, suggesting that current cultivars may be approaching the limits of their adaptive capacity. In Thailand, Arunrat et al. (2022) posit that a transition from rice cultivation to biannual maize planting and cassava production is becoming more advantageous in regions dependent on rainfall. For wheat, a non-traditional crop in Somalia, the already limited production has been further constricted by climate variability, emphasizing the need for importing to meet consumption demands. Moreover, sugarcane and rice, both water-intensive crops, are particularly vulnerable to changes in rainfall distribution. The evidence indicates that the frequency and intensity of droughts have disrupted irrigation-dependent farming systems, leading to significant drops in production. Arunrat et al. (2021) assert that, despite the adverse impacts of climate change on soil organic carbon levels and the valuation of carbon sequestration ecosystem services, organic rice cultivation is projected to face a lesser negative effect in comparison to traditional rice farming methods. In addition, banana cultivation, which thrives in humid conditions, has suffered due to the increased frequency of extreme weather events, leading to a decline in both yield and area cultivated. The resilience of bean production offers a glimmer of hope, as it demonstrates an upward trend despite climate adversities. Beans' adaptability to various climatic conditions makes them a viable option for diversification and enhancing food security.

4.5. Diagnostic tests

In search of unbiased outcomes, several diagnostic and model stability tests were performed, as presented in Table 7. The adjusted R-squared of all models is above 60%, which implies that more than 60% of the variations in major crop output are responsible for the selected regressors: average rainfall, temperature changes, GHGs, crop harvested area, and agricultural labour. The empirical results provide evidence that the model has no serial correlation issues, which indicates that errors in the entire model are not associated. Also, the Breusch-Pegan test (BPG) demonstrated that the volatility of the error terms is constant, which reveals that there is no heteroskedasticity. Besides, the data are normally and identically distributed, as indicated by the Jarque-Bera statistic. There is no evidence of misspecification of the functional form, which demonstrates the reliability of the model. The cumulative sum (CUSUM) and cumulative sum of squares (CUSUMSQ) of recursive residuals presented that most of the models are stable.

4.6. Granger causality test

Engle and Granger (1987) suggested setting the direction of the short – and long-run causal relations among the variables in the presence of cointegration. Table 8 provides an overview of the outcomes of the pair-wise Granger causality technique. The null hypothesis stating there is no Granger causation is rejected at the 1%, 5%, and 10% levels of significance. The empirical findings of Panel A assert that there is only a unidirectional causality from GHGs to sorghum production, which indicates that GHGs cause sorghum yield in Somalia. However, we could not reject the null hypotheses of no causal association between average rainfall, temperature changes, sorghum harvested area, agricultural labour, and sorghum production. It is remarkable from Panel B that there is no evidence to support the causal relationship between precipitation, temperature changes, GHGs, agricultural labour, and rice production. Nonetheless, we only observed a bidirectional causal linkage between rice output and rice harvested area, which proposes that rice yield and rice harvested area are interdependent.

In Panel C, the outcomes demonstrate that there is a unidirectional causality running from temperature changes to sugarcane output, which implies that deviations in temperature causally affect the yield of sugarcane. Moreover, the Granger causality results suggest that we reject the null hypothesis of no causality between sugarcane production and GHGs at the 1% significance level, indicating a unidirectional causal effect from sugarcane yield to GHGs. Additionally, the results reveal that there is a unidirectional causation running from agricultural labour to sugarcane production, which indicates that agricultural labour causally affects the yield of sugarcane. In Panel D, the results indicate a bidirectional causal association between average rainfall and banana output. This implies the crucial reliance of banana yields on rainfall changes in Somalia. The Granger causality results also reveal that there is unidirectional causality from banana production to temperature changes. In addition, the outcomes demonstrate there is a one-way causal effect from agricultural

Table 7. Diagnostic tests.

Test type	lnSOP	lnRP	lnSCP	lnBP	lnBEP
Adjusted R^2	0.95	0.696	0.883	0.648	0.932
Serial Correlation – LM test	0.261	3.081	0.85	1.632	1.933
	[0.610]	[0.079]	[0.654]	[0.201]	[0.164]
Heteroskedasticity – BPG test	11.235	15.68	16.238	10.703	10.252
	[0.795]	[0.547]	[0.576]	[0.933]	[0.673]
Normality – JB test	3.931	0.524	1.924	2.709	0.712
	[0.140]	[0.770]	[0.382]	[0.258]	[0.701]
Ramsey RESET Test	0.575	0.979	1.116	0.576	1.127
	[0.581]	[0.360]	[0.307]	[0.590]	[0.284]
CUSUM	S	S	S	US	S
CUSUM of squares	US	S	US	S	S

Notes: *P*-values are in the brackets [..].

Table 8. Pairwise Granger Causality Tests.

H_0: no granger causation	F-Statistic	Direction of causality
Panel A: Sorghum Model		
lnAP → lnSOP	0.634	No causation
lnSOP → lnAP	0.538	
lnTC → lnSOP	0.31	No causation
lnSOP → lnTC	1.549	
lnGHGs → lnSOP	3.982**	Unidirectional
lnSOP → lnGHGs	0.246	
lnSOHA → lnSOP	0.149	No causation
lnSOP → lnSOHA	2.34	
lnAL → lnSOP	0.005	No causation
lnSOP → lnAL	0.321	
Panel B: Rice Model		
lnAP → lnRP	0.372	No causation
lnRP → lnAP	0.352	
lnTC → lnRP	1.111	No causation
lnRP → lnTC	0.563	
lnGHGs → lnRP	2.443	No causation
lnRP → lnGHGs	0.868	
lnRHA → lnRP	2.532*	Bidirectional
lnRP → lnRHA	5.569**	
lnAL → lnRP	0.317	No causation
lnRP → lnAL	0.088	
Panel C: Sugarcane Model		
lnAP → lnSCP	1.254	No causation
lnSCP → lnAP	0.451	
lnTC → lnSCP	3.251*	Unidirectional
lnSCP → lnTC	0.636	
lnGHGS → lnSCP	1.178	Unidirectional
lnSCP → lnGHGs	8.141***	
lnSCHA → lnSCP	1.18	No causation
lnSCP → lnSCHA	0.434	
lnAL → lnSCP	4.881**	Unidirectional
lnSCP → lnAL	1.888	
Panel D: Banana Model		
lnAP → lnBP	4.297**	Bidirectional
lnBP → lnAP	2.453*	
lnTC → lnBP	1.223	Unidirectional
lnBP → lnTC	9.420***	
lnGHGs → lnBP	1.308	No causation
lnBP → lnGHGs	0.131	
lnBHA → lnBP	1.602	No causation
lnBP → lnBHA	0.564	
lnAL → lnBP	3.607**	Unidirectional
lnBP → lnAL	2.404	
Panel E: Beans Model		
lnAP → lnBEP	2.181	No causation
lnBEP → lnAP	1.831	
lnTC → lnBEP	0.085	Unidirectional
lnBEP → lnTC	10.528***	
lnGHGs → lnBEP	0.4	No causation
lnBEP → lnGHGs	0.037	
lnBEHA → lnBEP	0.2	Unidirectional
lnBEP → lnBEHA	4.253**	
lnAL → lnBEP	0.056	Unidirectional
lnBEP → lnAL	2.549*	

labour to banana production. This suggests that agricultural labour significantly contributes to banana yields in Somalia. Moreover, unidirectional causation from bean yield to temperature changes was observed in Panel E of Table 8. This outcome indicates that temperature variations are linked to bean output. Additionally, there is a unidirectional causality running from bean production to bean harvested areas and agricultural labour. This reveals that the production of beans affects the harvested areas as well as the agricultural labour producing it.

5. Conclusion and policy insights

The intricate interaction between climate change and major crop output stands as one of the most urgent challenges of our time. Acknowledging the wide variety of responses exhibited by different crops to climatic stressors, it is imperative to explore the consequences of climate-induced alterations in crop output. Concerning the trend of adverse climatic impacts on food security, this study uses multiple specifications to assess the effects of climate change on major crops, including maize, sorghum, rice, wheat, sugarcane, bananas, and beans, in Somalia using annual data from 1991 to 2019. To avert spurious regression, ADF and PP unit root tests were performed to determine the order of integration of the interested variables, and they produced a mixed order of integration, i.e. I(0) and I(1). Regarding this matter, this undertaking adopted the ARDL approach and Granger causality to explore the long-run association and causal linkage of the variables. The model passed all the diagnostic tests and the stability tests. The study reveals that crop production has been faced with serious difficulties as a result of both increasing temperatures and erratic precipitation patterns. Emphatically, precipitation increases have a constructive role in sorghum, sugarcane, and banana yields in the long run, although they hamper the production of beans. Moreover, rainfall has a favourable influence on beans, rice, and sugarcane output in the short-run, while altered precipitation patterns have proven to disrupt crop output for sorghum, sugarcane, and bananas.

On the other hand, the empirical results indicate that rising temperatures have a detrimental effect on crop yields in the long-run, particularly for sorghum, rice, and beans. The yield of rice and sorghum is positively related to temperature increases in the short run, although temperature variations reduce bean production. Crops like rice and bananas face heightened risks due to their substantial water requirements and sensitivity to extreme weather events. In the short-run, sorghum demonstrates a relatively higher resilience to water stress and temperature fluctuations, making it a potential adaptation option for farmers in Somalia. Another striking result from the study indicates that GHGs significantly enhance the yield of sorghum and bananas in the short and long-run. While environmental degradation increases rice and bean production in the long-run, it hampers their short-run yields, along with sugarcane. Also, all of the regressors are statistically significant to explain the positive role of crop harvested area in increasing the output of all selected crops in the long run, except for sugarcane, which was found to be statistically insignificant. In the short-run, the harvested areas of sorghum, rice, sugarcane, and bean production improve the yield of these crops.

Furthermore, agricultural labour has positive effects on the yield of bananas while reducing the yield of beans in the long-run. On the contrary, it reduces the production of major crops, i.e. sorghum and sugarcane, in the short – and long-run. The estimated ECT coefficients for sorghum, rice, sugarcane, bananas, and bean production show that any imbalance in the production of Somalia's major crops caused by short-run shocks is corrected by 75%, 41%, 77%, 31%, and 9% each year by the relevant explanatory factors. Remarkably, it was observed from Granger causality that GHGs cause sorghum production, although average rainfall, temperature changes, sorghum harvested area, agricultural labour, and sorghum production do not have a causal association. Besides, the evidence suggests the presence of bidirectional causality between rice output and rice harvested area. While temperature changes granger causes sugarcane output, there is a unidirectional causation from sugarcane yield to GHGs. Another striking finding from the Granger causality test is that agricultural labour causally affects the output of sugarcane and bananas. Moreover, average rainfall has a causal relationship in both directions with banana output. The Granger causality estimates also indicate a unidirectional causality from banana and bean production to temperature changes. Moreover, one-way causation runs from bean production to bean harvested area and agricultural labour.

Given the complexity of the issues that the study identifies, an integrated approach combining governments, academic institutions, non-governmental organizations, and local communities is essential for successful policy implementation. Thus, the following policy suggestions may be implemented to address the problems caused by climate change and enhance food security in Somalia. Firstly, given the diverse ways in which various crops react to shifting temperatures and precipitation patterns, an emphasis should be placed on developing and promoting climate-resilient crop types. To foster climate resilience, there is an urgent need for adopting climate-smart agricultural practices, developing and disseminating drought – and heat-tolerant crop varieties, and improving water management systems. In this endeavour, governments and international organizations need to fund research that might encourage farmers to use more productive and resilient methods and technology. Secondly, improving irrigation infrastructure may function as a water stress buffer since changing precipitation patterns and rising temperatures have a detrimental influence on agricultural production. The creation of effective irrigation systems may aid in ensuring a steady supply of water for crops during dry seasons. Thirdly, in order for farmers to make wise choices regarding planting, harvesting, and pest control, they should have access to timely and accurate weather predictions as well as early warning systems. This significantly enhances sustainable food production by enabling farmers to preemptively adjust agricultural practices, thus mitigating risks, optimizing resource use, and improving crop yields. Fourthly, it is essential to undertake sustainable land management methods in order to counteract the detrimental impacts of environmental deterioration on crop cultivation. This includes practices that may promote long-term production, including crop rotation, cover cropping, and decreased tillage. Fifthly, it is important to design agricultural labour efficiency measures that take crop yields and labour allocation into account. This can include incorporating machinery and contemporary agricultural techniques to guarantee a higher yield while properly employing labour.

Author contributions

Abdikafi Hassan Abdi: Conceptualization, data collection and analyzing, writing the introduction, improving and editing the original draft. Mohamed Okash Sugow: Writing the methodology. Dhaqane Roble Halane: Writing the the literature review.

Data availability

The datasets used and/or analyzed during the current study are available from the author on reasonable request.

Disclosure statement

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Ethical approval

This study follows all ethical practices during writing. We declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere.

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