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Climate change, land, water and food security: Perspectives from Sub-Saharan Africa

Edited by
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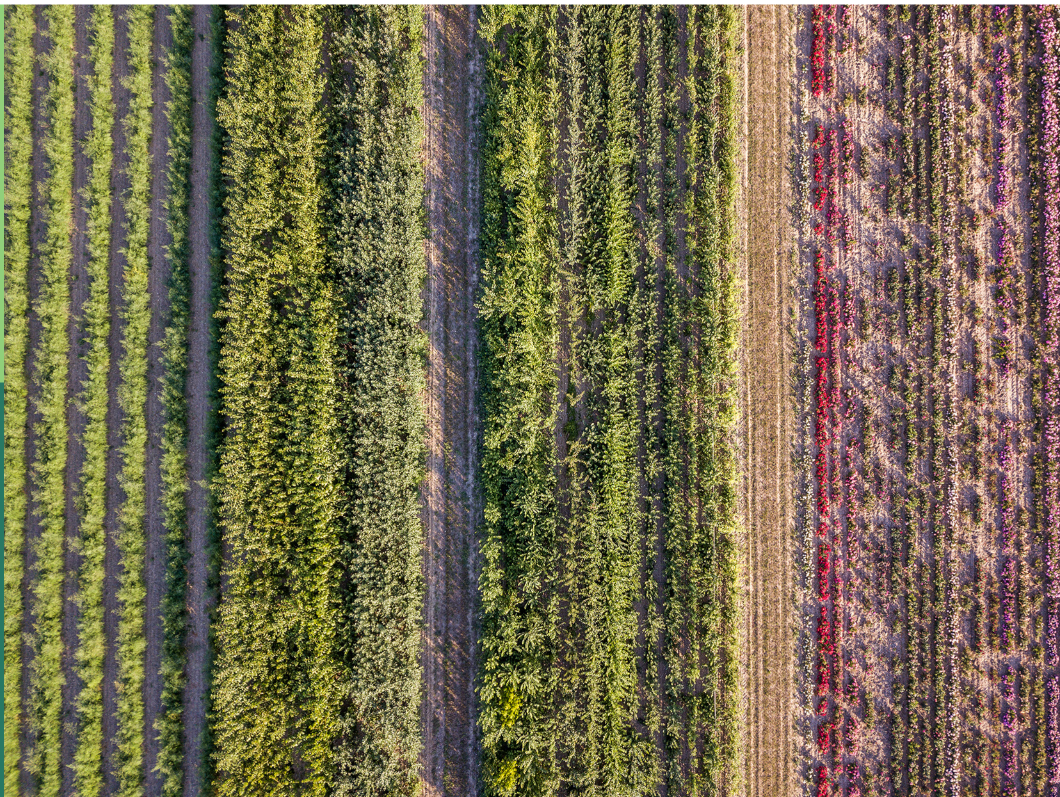

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Climate change, land, water and food security: Perspectives from Sub-Saharan Africa

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Table of contents

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Editorial: Climate change, land, water and food security: perspectives from Sub-Saharan Africa

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Editorial on the Research Topic
Climate change, land, water and food security: perspectives from Sub-Saharan Africa

The narrative of human civilization is intricately woven around the fabric of environmental factors. Whilst several societies have devised diverse technologies to control their environment and mitigate the negative impact of environmental elements, the confluence of environmental factors continues to be a core issue in the ability of society to thrive. In recent years, climate change, water crisis, land scarcity, and food security have become increasing concerns for academics, political scientists, and the media. These, coupled with the rising population, increasing urbanization, changes in consumption patterns, and industrialization continue to exert enormous pressure on the environment, which further aggravates food insecurity in unprecedented proportions (Biswas and Tortajada, 2019). This has been championed by prominent international organizations in international fora such as the Millennium Development Goals, the Sustainable Development Goals, the Paris Agreement (Paris Climate Accords) of the Intergovernmental Panel on Climate Change (IPCC), and the Global Assessment Report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) amongst others, advocating for the effective governance of environmental resources to mitigate the effects of the climate crisis and ensure food security. However, forecasts in recent years by international organizations have been grim. For example, climate change is expected to adversely impact the four pillars of food security—availability, access, utilization, and stability [World Economic Forum (WEF), 2022]. Furthermore, the Special Report on Climate Change and Land (SRCCL) acknowledged that ∼21%−37% of total greenhouse gas (GHG) emissions are from food systems. Food system emissions comprise emissions from agriculture, land use, storage, transport, packaging, processing, retail, and consumption activities. This editorial explored the intricate interactions between climate change-water-land-food security.

Recent evidence suggests that climate crises adversely affect the global economy, particularly, agriculture, and this has compromised food production in Africa, with serious effects on the livelihood of smallholder farmers [Tantoh et al., 2022; World Economic Forum (WEF), 2022]. Importantly, ownership and access to sufficient arable land in countries like South Africa, Zimbabwe, and Namibia, among others have prevented smallholder farmers from improving food security. Smallholder farmers in South Africa, for example, have access to <2 hectares of land (Lowder et al., 2016).

Furthermore, the adaptation of smallholder farmers to climate change to enable improved livelihood earnings has received inadequate responsiveness from public authorities. Given the diversity of Sub-Saharan Africa, an understanding of the differentiated effects of climate and environmental changes on the water-land-food security nexus on its societies at different stages of development demands critical investigation. This comes with implications for the continent's success in achieving its sustainable development imperatives as espoused by the UN SDGs and the related "Leave No One Behind" agenda, coupled with the African Union's Agenda 2063 "The Africa We Want." This is in light of increasing evidence of climate-induced impacts on land-water-food security, which galvanizes advocacy toward climate justice coupled with addressing loss and damage. Nevertheless, collective measures to address climate change and diverse adaptation strategies are still lacking given the pace and scale of climate impacts. As the final decade of action of the SDGs gains traction, it is imperative to understand the dynamics of local climate and responses to climate variability and changes in the context of the water-land-food security nexus. Given that climate-induced extreme events are expected to increase in frequency and intensity, novel measures are vital and are informed by innovative research.

This editorial comprises findings of the complex interactions between climate change-water-land-food security nexus from different parts of sub-Saharan Africa. Water and land, for example, are central to ensuring effective and productive rural economies. Furthermore, they are vital to ensuring sustainable and productive rural economies. However, women, for example, who are directly responsible for water and food production at the household level, have limited access and restricted formal rights which hinder food security and exacerbate their vulnerability. Gender roles and their implications in climate change-water-land are therefore imperative for food security (Tantoh et al., 2021). Importantly, how the nexus operates in an environment of the increasing climate crisis, which increases the pressure on land, water scarcity, and food insecurity calls for a change that is essential for sustainability (Siakwah and Torto, 2022). Thus, understanding these relationships to enable sustainability requires a purposeful approach to the nexus. This facilitates the comprehension of the multi-level, contradictory, and diverse interests between and across the systems. However, the effects of climate change on food production coupled with growing inconsistencies in local knowledge systems have obliged some farmers to rely on seasonal climate forecasts to make informed decisions. This is because seasonal climate forecasts have improved food production in some rural communities, while others refuse to trust in this local intelligence and ill timing of forecast dissemination. Thus, demystifying the dynamics that hinder the use of seasonal climate forecasts is essential for dismantling the barriers that undermine the use of seasonal climate forecasts which could obstruct the attainment of the UN SGGs two and five (Ebhuoma, 2022). In the same vein, differentiated agro-climatic zones have greatly influenced crop production and food security among smallholder farmers (Laishram et al., 2022). Numerous adaptation measures that address climate variability and build upon improved land and water management practices have the potential to reinforce resilience in the water-land food security nexus.

The findings and recommendations of these articles are timely and pertinent and should be of interest to our audience.

Author contributions

HBT: conceptualization, visualization, design of research instruments, and writing original draft.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Climate Change, Land, Water, and Food Security: Perspectives From Sub-Saharan Africa

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The current and projected warming of the earth is unequivocal with humans playing a strong role as both perpetrators and victims. The warming on the African continent is projected to be greater than the global average with an increased average temperature of 3–6°C by the end of the century under a high Representative Concentration Pathway. In Africa, the Sub-Saharan region is identified as the most vulnerable to the changing climate due to its very low capacity to adapt to or mitigate climate change. While it is common to identify studies conducted to assess how climate change independently impacts water, land, or food resources, very limited studies have sought to address the interlinkages, synergies, and trade-offs existing between climate change, water, land, and food (WLF) resources as a system in Sub-Saharan Africa (SSA). The climate change and WLF security nexus, therefore, seeks to address this shortfall in literature and subsequently serve as a relevant source of information for decision-making and policy implementation concerning climate change mitigation and adaptation. In this study, 41 relevant studies were selected from Web of Science, Google Scholar, ResearchGate, and institutional websites. We provide information on the independent relationships between climate change and WLF resources, and further discuss the existing inter-linkages between climate change and the WLF security in SSA using the nexus approach, with recommendations on how decision making and policy implementations should be done using the climate change and WLF security nexus approach.

Keywords: climate change, water depletion, land degradation, food security, nexus approach, multidisciplinary approach

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INTRODUCTION

Climate change as defined by the Intergovernmental Panel on Climate Change (IPCC) is "a change in the state of the climate that can be identified (e.g. using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer" [Intergovernmental Panel on Climate Change (IPCC), 2007]. The change in the global climate has been reported to be as a result of both human activities and natural variabilities. The United Nations Framework Convention on Climate Change (UNFCCC) in their definition emphasizes that the changing climate is directly or indirectly attributable to human activities

(UNFCCC, 2011). The observed changes in climate at the global, continental, and sub-continental levels include an increase in air and ocean temperatures, sea-level rise, decrease in snow and ice extent, increase and decrease in precipitation, changes in terrestrial and marine biological systems, ocean acidification [Intergovernmental Panel on Climate Change (IPCC), 2007; UNFCCC, 2011].

These observed changes in the climatic system have been mainly induced by the warming process of the climate system. This warming process is described as global warming which involves the increase in the global temperature due to the increased emissions of Greenhouse Gases (GHGs) coming from human activities [Intergovernmental Panel on Climate Change (IPCC), 2014]. The major contributing GHGs assessed by the UNFCCC include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphurhexafluoride (SF_6) Intergovernmental Panel on Climate Change (IPCC), 2007; Bruhwiler et al., 2021. Notwithstanding the increased number of policies developed to mitigate climate change, there has been absolute increases in total anthropogenic GHGs over the period of 2000 to 2010, reaching a total of 49 ± 4.5 $GtCO_2$-eq/yr^3, with the major contribution (about 78%) being CO_2 emissions from fossil fuel combustion and industrial processes.

From 1880 to 2012, there has been an observed increase in the average temperature of the global land and ocean surface by 0.85 [0.65–1.06]°C [Intergovernmental Panel on Climate Change (IPCC), 2014]. The global mean surface temperature by 2017 was ascertained to be around 1°C higher than the preindustrial values with an increase of 0.2°C/decade (Bruhwiler et al., 2021). It is projected that by the end of the twenty-first century, the global surface temperature will likely exceed 1.5°C with higher frequencies and longer durations of heatwaves based on RCP4.5, RCP6.0, and RCP8.5 scenarios [Intergovernmental Panel on Climate Change (IPCC), 2014]. Changes in precipitation will, however, be experienced differently across the different regions of the globe (Giorgi et al., 2018). An increase in annual precipitation will be experienced in regions in the high latitudes and the equatorial Pacific under the RCP8.5 scenario, whereas regions in the dry mid-latitude and subtropics will experience a decreased annual precipitation. The regions in the wet mid-latitude and wet tropics will also experience extreme annual precipitation [Intergovernmental Panel on Climate Change (IPCC), 2014; Giorgi et al., 2018].

From a continental view, the warming in the African continent is projected to be greater than the global average with an increased average temperature of 3–4°C over the twenty-second century (Thompson et al., 2010; Zewdie, 2014). The changes in precipitation to be experienced on the African continent at the end of the twenty-first century is however expected to be unique across the different regions (Niang et al., 2014). The West African region is expected to experience a slight or no change in heavy precipitation, while precipitation in the Eastern and Central African region is projected to increase (Niang et al., 2014; Girvetz et al., 2019). For the Southern and Northern African regions, there is a projected decrease in total precipitation with Southern Africa recording an increase in heavy precipitations (Niang et al., 2014).

In Africa, the Sub-Saharan region is identified as the most vulnerable to the changing climate (Ringler et al., 2010; Thompson et al., 2010). This is due to the region's very low adaptive capacity in connection to the acute levels of poverty and the limited facilities needed to mitigate and/or adapt to the changing climate (Ringler et al., 2010). Sub-Saharan Africa (SSA) is a region that greatly depends on precipitation to be able to provide the water, food, and energy needs of its people (Thompson et al., 2010). For instance, the prevalence of rain-fed agriculture in most of the region makes its food systems highly sensitive to the changing patterns in precipitation (Thompson et al., 2010).

In SSA, many studies have presented the current and future impacts of climate change on either water resources, land resources or food systems, and how these impacts further affect the lives of people who depend on them. Whenever we discuss the issue of climate change, it is a fact that nature will suffer from the consequences, but we need to realize that humans who are the main perpetrators are equally the main victims of climate change. This is because our well-being depends on nature and its services. The United Nations enlist food, clean water, and clean air as basic needs for our existence, indicating that at any point in time, these resources should be available at adequate quantity and quality, and accessible to all (UN Department of Economic Social Affairs, 2018).

In the past decade, scientists and policymakers have come to realize that the relationship between climate change and water resources, land, and food resources are not unidimensional but multidimensional. This situation therefore calls for a nexus approach that addresses the inter-connectedness, synergies, and trade-offs existing between climate change and the water, land, and food (WLF) resources, which in early times were considered independently. While studies have sought to present the climate change and WLF security nexus in Africa, efforts in realizing it in the policymaking process is less pronounced in SSA. This study seeks to bring to light the current and future impacts of climate change on WLF resources, as well as the relationship between climate change and the WLF security nexus in SSA, and further suggests strategies needed to address these issues from a multidimensional perspective in the policymaking process.

METHODS

Studies published from the period of 2005 to 2021 were extracted from databases using the keywords: "Climate change in 'country X"' where "country X" represents a country located in the SSA region. Databases used for the extraction of studies and reports included Web of science, Google Scholar, ResearchGate. Reports on the impacts of climate change on either water, land, and/or food resources in Africa were also extracted from websites of international organizations such as IPCC, UNFCC, and the FAO. Out of 136 studies which were initially extracted, 41 were selected as relevant for this study after their abstracts were screened. Out of the 41 studies which were selected, 28 of them were used in preparing the sections Impacts of Climate Change on Water, Land and Food Resources in SSA to Climate Change and the WLF Security Nexus in SSA of this study. **Table 1** provides a summary of these 28 studies.

IMPACTS OF CLIMATE CHANGE ON WATER, LAND AND FOOD RESOURCES IN SSA

Climate Change and Water Resources in SSA

Although anthropogenic activities such as changes in land use/cover, diversions, and hyper-withdrawal of water from rivers and lakes, and increased pollution and sedimentation directly impact freshwater ecosystems in SSA, climate change also contribute to their degradation. The contributing impacts of climate change on freshwater ecosystems in SSA are evidenced by elevated water temperatures reported in surface waters of Lakes Kariba, Kivu, Tanganyika, Victoria, and Malawi (Niang et al., 2014). The water capacity of some major water systems such as lakes and rivers in SSA is expected to reduce in response to the decrease in precipitation and an increase in evaporation (Bates et al., 2008). However, studies have suggested that climate change in the region will have an overall modest effect on future water scarcity when compared to other anthropogenic activities (Niang et al., 2014).

The projected changes in water resources in response to climate change and other drivers are different when considering the sub-regions of the SSA. For instance, under the A2 and B2 scenarios, it is projected that there will be a decrease in surface water discharge and seasonal runoff volumes in the Upper Nile Basin in Uganda and the Lake Tana Basin in Ethiopia, respectively, by the 2080s (Niang et al., 2014). Water shortages are also estimated for the Okavango Delta, the Breede River in South Africa, and the downstream of the Rozva dam in Zimbabwe (Niang et al., 2014). However, an increased flow is projected to occur in the Mara, Nyando, and Tana Rivers in Eastern Africa during the second half of this century (Niang et al., 2014).

The modeling of how climate change impacts water resources in Western Africa is constrained by the significant uncertainties in models used in reference to the future precipitation of the region. For instance, while higher future precipitation is estimated in the Niger River Basin (A1, A2, and B1 scenarios), a strong seasonal component with reduced precipitation in the basin is also projected during the rainy season and increased precipitation during the dry season (A1B scenario). The Volta Basin is projected to experience a slight mean increase in precipitation and the Bani River Basin in Mali is estimated to have significant decreases in runoff (A2 scenario) due to reduced precipitation. In the Congo Basin, the impact of climate change on total runoff is projected to be minimal under A2 scenario (Niang et al., 2014).

The occurrence of drought is another important environmental issue that is highly pronounced in some sub-regions of SSA. Drought is a component of the natural variability in climate on the African continent, with quite high intensities at monthly, yearly, decadal, or century timescales. Some studies have reported on how climate change, aerosol emissions, land use practices, and subsequent land-atmosphere interactions, have led to mechanisms inducing droughts (Masih et al., 2014; Bhaga et al., 2020). Moreover, El Niño–Southern Oscillation (ENSO) and sea surface temperatures (SSTs) are considered as key factors influencing drought across SSA (Masih et al., 2014). It is however important to note that predicting drought is a slow and difficult process due to the overarching complexities related to its causes, timescale, extent, and timing on different spatial and temporal scales (Ndehedehe et al., 2020).

In the recent past, many extreme and extended droughts such as the 1999–2002 drought in North-western Africa, 1970s and 1980s droughts in Western Africa (Sahel), 2010–2011 drought in Eastern Africa (Horn of Africa), and 2001–2003 drought in Southern and South-Eastern Africa, were recorded (Masih et al., 2014). Since 2005, the rate of recurrence of drought in Eastern Africa has increased from one in every 6 years to one every 3 years. Between 2008 and 2010, over 13 million people in Eastern Africa have been affected by droughts. Moreover, the Horn of Africa which includes Djibouti, Eritrea, Ethiopia, and Somalia, have experienced extreme droughts from 2010 to 2011, caused issues of food insecurity that affected about 20 million people, leading to a significant loss of lives. Drought in Somalia, Kenya, and Ethiopia, contributed to socio-economic instabilities, where Somalia alone recorded 250,000 deaths during the same period (Bhaga et al., 2020). There is medium confidence that droughts will intensify in East and Southern Africa during the twenty-first twenty-first in some seasons, because of reduced precipitation and/or increased evapotranspiration (Niang et al., 2014).

Climate Change and Land Resources in SSA

Land use/cover change refers to any human activity and intervention that results in a change of a particular land use/cover into another land use/cover or the intensification of an existing land use/cover (Antwi-agyei et al., 2019). It has been presented that changes in land surface features such as albedo, evapotranspiration, and primary production contribute to changes in climate at different geographical scales, and the dynamics in atmospheric carbon concentrations (Linderman et al., 2005). A major consequence is when the livelihoods of people are negatively affected, and this is highly noticeable in SSA where most households rely on land-based activities for their well-being (Antwi-agyei et al., 2019).

Changes in land use/cover and climate have led to observed changes in the distribution and dynamics of different types of terrestrial ecosystems in SSA. Some of the terrestrial ecosystems include grasslands and shrublands, savannas and woodlands, and forests. The increasing intensity of anthropogenic activities in forested areas has led to a decrease in the areal extent of natural vegetations (Gonzalez et al., 2012). Observations have been made on a complex set of spatial shifts in the distribution of remaining natural vegetation types (Niang et al., 2014). Some plants and animal species which are specialist to certain ecological conditions in the SSA are identified to be vulnerable to

TABLE 1 | Summary of some selected studies.

Study	Area of study	Objective of study
Antwi-agyei et al. (2019)	Owabi Reservoir Catchment (Ghana)	Land use and land cover changes
Allison et al. (2009)	Angola, DRC, Mauritania, and Senegal	Vulnerability of national economies to the impacts of climate change on fisheries
Bhaga et al. (2020)	Sub-Saharan Africa	Impacts of climate variability and drought on surface water resources
Bonsor et al. (2010)	Africa	Potential impact of climate change on water supplies
Chiarelli et al. (2016)	Africa	Climate change and large-scale land acquisitions and its future impacts on water resources
Deen-Swarray et al. (2020)	Africa	Sustainable agriculture and climate change issues
Descheemaeker et al. (2016)	Sub-Saharan Africa	Climate change adaptation and mitigation in smallholder crop—livestock systems
Food and Agriculture Organisation (FAO) (2005)	Sub-Saharan Africa	Impact of climate change, pests, and diseases on food security and poverty reduction
Gezie (2019)	Ethiopia	Farmer's response to climate change and variability
Girvetz et al. (2019)	Africa	Future climate projections
Glover and Jones (2018)	Mozambique	Commercial farming and land acquisition
Gomes (2020)	Mozambique	Land deals, climate vulnerability, and adaptation
Gonzalez et al. (2012)	Sahel Africa	Impacts of climate on tree species
Herrmann and Mohr (2011)	Africa	Classification of rainfall seasonality regimes
Jaramillo et al. (2011)	East Africa	Impacts of climate change on coffee berry borer and coffee production
Leauthaud et al. (2013)	Tana River Delta (Kenya)	Impact of changing water resources on wetland agro-ecological production systems
Linderman et al. (2005)	Africa	Land-cover change and vegetation dynamics
Mapulanga and Naito (2019)	Malawi	Effect of deforestation on access to clean drinking water
Mupangwa et al. (2016)	Southern Africa	Soil water conservation in semi-arid cropping systems
Ndehedehe et al. (2020)	Sahel Africa	Evolutionary drought patterns and their teleconnections with low frequency climate oscillations
Nhemachena et al. (2020)	Southern Africa	Climate change impacts on water and agriculture
Niang et al. (2014)	Africa	Climate change impacts, adaptation, and vulnerability
Nicholls et al. (2008)	Eastern Africa	Managing agricultural pests, diseases, and weeds under climate change
Olisah et al. (2020)	Africa	Occurrence of organochlorine pesticide residues in biological and environmental matrices
Ringler et al. (2010)	Sub-Saharan Africa	Climate change impacts on food security
Thompson et al. (2010)	Sub-Saharan Africa	Climate change impacts on food security
Ukpe et al. (2020)	West Africa	Crop and livestock production responses to rainfall and temperature variation
Zacarias (2020)	Sub-Saharan Africa	Global bioclimatic suitability for the fall armyworm and potential co-occurrence with major host crops under climate change scenarios

limited levels of resources caused by climate change (Sintayehu, 2018). For instance, in Ethiopia, the Ethiopian wolf (*Canis simensis*) is said to be at risk of local extinction due to the longer dry periods with reduced availability of water (Sintayehu, 2018).

While there have been net decreases recorded in woody vegetation in Western Africa, the Central, Eastern, and Southern Africa have recorded net increases in their woody vegetation. Even though the principal driver of these changes is land use/cover change caused by human activities such as the expansion of crop production and livestock rearing activities, and fuelwood harvesting, climate variability, climate change, and interactions between them drivers have significant added and interacting effects (Niang et al., 2014). Rural livelihoods in SSA are frequently affected by changes in land use/cover. These impacts are commonly intensified by the dependence of rural households on agricultural activities that are significantly reliant on the climate (Antwi-agyei et al., 2019). Drought resulting from changes in land use/cover and climate is considered as a key cause of land degradation, aridity, and desertification, further producing immense socio-economic impacts such as large-scale migration, and famine in the semi-arid sub-region of SSA (Masih et al., 2014). Poor smallholder farmers in SSA are reliant on land to gain access to relevant input resources. However, acquiring access to arable lands for crop production has been on a diminishing trend due to the pressure from the growing population, exacerbating land degradation due to climate change, and more importantly land grabbing (Deen-Swarray et al., 2020).

Climate Change and Food Resources in SSA

In SSA, agricultural activities which depend on rain account for over 95% of the total agriculture which takes place on land (Mupangwa et al., 2016). Future climatic changes occurring in SSA may lead to the shortening of crop and fodder growing periods in Western and Southern Africa by an average of 20% by 2050, resulting in a 40% decrease in cereal yields and a drop in the biomass of cereal used for livestock rearing. Changes in length of the growing season with a propensity toward decreased growing season length are also projected, however, with some areas having the potential to have longer growing seasons (Niang et al., 2014).

Estimated losses in crop yield resulting from climate change during the middle of the twenty-first-century range from 18% for Southern Africa to 22% totaled across SSA. However, in Eastern Africa, warming at high elevation locations could promote the production of maize (Niang et al., 2014).

The impacts of climate change on agriculture is not only limited to crop production but also includes livestock rearing and other activities related to agriculture. Climate variables such as air, temperature, humidity, wind speed and other climate factors are projected to directly influence the performance of livestock, such as growth, milk production, wool production, and reproduction. Chickens are largely at risk of climate change due to the low thermal window beyond which reproduction and growth are negatively affected. Moreover, projected increased warming can be highly pronounced within intensive poultry practices as animals are reared in enclosed spaces (Gezie, 2019). Changes in climate can also influence the quantity and quality of provender (pasture, forage, and grain) and also the occurrence and spread of livestock diseases and parasite (Ukpe et al., 2020). In the transition zones which include the West African Sahel and coastal and mid-altitude areas in Eastern and South-eastern Africa, it is projected that livestock rearing will replace mixed crop-livestock systems by 2050 (Niang et al., 2014).

CLIMATE CHANGE AND THE WLF SECURITY NEXUS IN SSA

The use of the nexus approach in addressing issues of climate change helps to appreciate how WLF resources are interconnected in a two- and/or three-dimensional way. Some studies have indicated how water depletion in freshwater ecosystems and wetlands impacts crop production, fishing, and livestock rearing present in SSA (Leauthaud et al., 2013). Others have shown how improper agricultural practices can impact land and water resources (Barnhoorn and van Dyk, 2020; Olisah et al., 2020). Agriculture is known to be a major source of food and livelihoods in many local communities in SSA. With the majority of these communities depending on precipitation as a major ingredient for higher yields, crop production commonly takes place during wet seasons of the year (Thompson et al., 2010; Herrmann and Mohr, 2011). However, depending on the location and local weather conditions, an area within a country may experience either a unimodal, bimodal or multimodal wet season. For instance, most of the seasonal rainfall regimes (>90%) experienced by regions in SSA are single wet season regimes. However, the central Congo Basin, eastern Madagascar, and small areas of the Guinea coast do experience an all year round wet season, while dual wet-season regimes are most common in East Africa (Herrmann and Mohr, 2011).

In countries with a single wet season, crop production that takes place during the dry season is done with irrigation system interventions. The local communities build reservoirs or depend on riverine and lacustrine systems for irrigation of their crop fields. Nevertheless, this practice of irrigation does no prove to be sustainable as the reservoirs and freshwater ecosystems are prone to depletion with a projected increase in surface water and air temperatures and a decrease in precipitation in some regions of SSA (Niang et al., 2014). Such a situation is evident in Southern Africa where during 2015, 9 million ha which represents only 9% of the total cultivated land of 107 million ha was irrigated. However, the volume of water extracted for these irrigation activities represents over 70% of the available freshwater resources, of which countries like South Africa, Zimbabwe, Mozambique, and Tanzania are major contributors (Nhemachena et al., 2020). This issue is even more pronounced when the people have to depend on the limited water resources for other key uses such as drinking, cooking, or additional domestic activities.

In the 31st session of the Committee on World Food Security, the Food and Agriculture Organisation (FAO) (2005) indicated that in developing countries which includes countries in SSA, climate change would lead to an increase in lands that are arid and lands with moisture stress, thereby causing a decrease in cultivable rainfed land, with a consequent decline in cereal production. The potential impacts of climate change on lands and the growing population in SSA will eventually cause increased extraction of the limited freshwater and groundwater resources to meet the increased demands on food and water resources (Bonsor et al., 2010).

Countries in the north and east of the Southern Africa region is projected to experience a reduced potential output of cereal production by 50% or more by 2080 in response to the future events of increased water scarcity caused by climate change. Moreover, while countries in the west of the Southern Africa region are expected to experience a decrease of 15–50% in agricultural productivity, countries such as Angola, Democratic Republic of Congo (DRC), parts of Zambia and Mozambique, positioned in the further north will experience an increase of 25% or more (Nhemachena et al., 2020). Between the period of 2011 to 2020, countries like Mauritania, Mali, Cote d'Ivoire, Madagascar, and Lesotho have experienced poor rains and droughts leading to poor agricultural harvests, loss of livestock, an increase in food prices, starvation, food shortage, famine, drying up of reservoirs, and dams, affecting a great number of people. In Lesotho, it is projected that more than 30% of the population will experience acute food insecurity due to ongoing drought conditions (Bhaga et al., 2020).

Climate change resulting in the depletion of freshwater ecosystems with soil water over the years has caused the reduction in fishing and livestock-rearing activities in some countries in SSA. Several climate variables such as changes in air and water temperatures, precipitation, river flow, nutrient levels, storm frequency and intensity, and flooding occurring in freshwater ecosystems can influence fisheries through a range of direct and indirect pathways (Allison et al., 2009). Out of the 132 countries which are vulnerable to climate change-driven impacts on fisheries, Angola, DRC, Mauritania, and Senegal were found in the top five (Allison et al., 2009; Niang et al., 2014). Projected changes in temperature and precipitation will also lead to a reduction in the quantity and quality of biomass in pasturelands and drinking water needed for livestock rearing. This situation will be more obvious during prolonged dry seasons where the consequences could be increased reduction in livestock fitness and number with farmers shifting to more resilient breeds or crop farming (Descheemaeker et al., 2016).

Land deals, mostly in the form of leases or concessions provided on a long-term basis, have appeared as a significant component of land use/cover change across SSA over the last decade (Gomes, 2020). Among the total land area of about 50 million hectares (ha) in developing countries being targeted by external investors, SSA possesses the largest amount (Glover and Jones, 2018). In most cases, lands acquired by external investors in SSA are used to cultivate plants useful for biofuel production, which is identified as a strategy in mitigating climate change (Gomes, 2020). In Mozambique, the rush of land deals has generated controversies, pointing out its potential impacts on freshwater ecosystems and arable lands, restricting local communities of access to freshwater ecosystems on leased lands, thereby reinforcing their vulnerability to climate change (Glover and Jones, 2018; Gomes, 2020). When lands are available for the local communities located in resource-poor countries, it offers them a means to increase their limited natural resources for food production and may in turn act as a safeguard to potential future impacts of climate change on food security (Chiarelli et al., 2016).

Terrestrial ecosystems such as forests, riparian vegetation, grasslands, savannas, and woodlands are identified to contribute positively to the hydrological cycle. It is evident that the observed and projected changes in the distribution and dynamics of the different terrestrial ecosystems in SSA will add to the existing impacts of climate change on freshwater ecosystems. Sub-Saharan Africa has experienced rapid deforestation of about 3.4 million ha/year between 2000 and 2010 with Malawi having the highest deforestation rate (Mapulanga and Naito, 2019). The primary drivers of deforestation in SSA are the expansion of agriculture, livestock grazing, and fuelwood harvesting (Niang et al., 2014). With increasing rates of deforestation in SSA, the carbon storage and sequestration capacity of trees reduces, causing increased concentration of atmospheric CO_2 and higher rates of warming events. The impacts of deforestation on freshwater ecosystems include reduced infiltration, increased sedimentation affecting water quality, increased soil erosion, and increased evaporation of neighboring surface water ecosystems (Mapulanga and Naito, 2019). This situation of depleted quantity and quality of freshwater ecosystems goes a long way to negatively affect crop and livestock-rearing activities, and further limits the available water for domestic use, all amounting to food and water insecurity.

Deforestation exposes the land to soil erosion and the loss of available soil nutrients and moisture necessary for crop production and the production of pasturelands useful for livestock rearing. Deforestation occurring in riparian vegetation exposes freshwater ecosystems to direct sunlight, increasing the risk of surface evaporation as water and air temperature continues to increase in SSA. In regions of limited arable lands available for crop production, farmers will be obliged to adopt the use of fertilizers to improve crop yields. During events of heavy precipitation, as predicted to occur in Eastern African countries (Niang et al., 2014), increased runoffs from the farms reaching neighboring freshwater ecosystems pose the risk of water pollution, affecting water quality and aquatic biodiversity.

Climate change in connection with other environmental and production factors could increase crop loss generated by pests, weeds, and diseases. In the highland regions of Eastern Africa, warming could lead to crop pests extending their range into areas that are limited by cold temperatures (low confidence). For example, in highland areas of Eastern Africa where Arabica coffee is produced, trends in warming may cause the coffee berry borer (*Hypothenemus hampei*) to become a severe threat in regions of Ethiopia, Kenya, Uganda, Rwanda, and Burundi which are involved in coffee production (Jaramillo et al., 2011). Increases in temperature in highland areas of Eastern Africa which are involved in banana production may increase the risk of altitudinal range extension of the highly destructive burrowing nematode, *Radopholus similis* (Nicholls et al., 2008). Another study conducted by Zacarias (2020) projected that there is an enormous climatic potential for the spread of the fall armyworm (*Spodoptera frugiperda*), with potential increases in SSA, particularly the northern border of SSA.

To deal with the issue of pest, weeds and diseases in farms, farmers are forced to make use of pesticides, weedicides, herbicides, or fungicides. The improper handling of these chemicals by farmers and other end users have been responsible for the high level of occurrence in the freshwater and terrestrial ecosystems, hence posing threat to human health and the ecosystem at large (Olisah et al., 2020). In South Africa, significant concentrations of endosulfan, DDTs and other pesticides were reported to be present in Lourens River, Hex River, and Pongolo floodplain (Olisah et al., 2020). Barnhoorn and van Dyk (2020) also reported the occurrences of herbicides such as Dacthal, metribuzin, simazine, tebuthiuron, terbuthylazine, and the fungicides azoxystrobin, carbendazim, epoxiconazole, metalaxyl (Ridomil), propiconazole, pyrimethanil and thiabendazole in the Roodeplaat Dam of South Africa. Other studies conducted in Lake Bosomtwe and Lake Volta of Ghana, Tana and Sabaki of Kenya, Lake Victoria of Tanzania, Ogbese River of Nigeria, and Lake Ziway in the Ethiopian Rift Valley basin reported significant concentrations of pesticides in water and sediment samples (Merga et al., 2020; Olisah et al., 2020). In other instances, high levels of pesticides were recorded in soil samples collected from farmlands located in Upper Awash of Ethiopia and Ngarenanyuki, Vikuge Farm, and Lake Victoria of Tanzania (Olisah et al., 2020).

CONCLUSIONS AND RECOMMENDATIONS

This study has presented the current and future trends of climate change in SSA. On one hand, it examines the relationship between climate change and the components of the WLF security nexus independently, and on the other hand, it provides an overview of how interconnected the components of the WLF security nexus are, and how when climate change impacts one of them, the others can also directly or indirectly suffer the consequences. The nexus approach which presents the interlinkages, trade-offs, and synergies existing between water, land and food resources suggests the need for developing mitigation and adaptation strategies toward climate change in a comprehensive manner. In other words, policies developed to tackle climate change impacts on either of the three components of the nexus must be able to have the other components in the view. For instance, water resource management strategies must make sure land resources such as forest ecosystems and food resources from agriculture are not negatively impacted in both present and future time, and vice versa.

This is a very complex system, and therefore calls for a trans-disciplinary team which is a diverse group of professionals and experts from the sectors of climate change, water resource management, natural resource management, biodiversity and ecosystem conservation, sustainable agricultural production, environmental protection, economics, sociology, and local communities (**Figure 1**), working together across their disciplines to tackle the issues relating to climate change and the WLF security nexus. The decision-making process among stakeholders must however be complemented by using models of systems approach. For instance, the development of the Climate, Land, Energy and Water (CLEWS approach) modeling framework by the International Atomic Energy Agency (IAEA) in 2009 helps to employ a combined use of modeling tools available for the components of the WLF security nexus and climate change (Welsch et al., 2014). The model which is interdisciplinary in nature helps stakeholders to quantify the existing interactions between the components of the WLF security nexus, and also provide a clear definition of data exchange between these components/stakeholders. The modeling tools are then calibrated using historical climatic data (preferably done singly by each model before assessing interlinkages). Future scenarios which are represented in the modeling tools are therefore used to assess implications by comparing current data with future development pathways and eventually the results are interpreted and implemented (Welsch et al., 2014).

One of the strengths of the CLEWS approach is that it is not inherently system-biased, indicating that no system is given priority over the other (Ramos et al., 2021). Over the years, the drive of the CLEWS approach by institutions through multiple applications has contributed to closing the gap between science and policy (Ramos et al., 2021). Amidst the benefits being derived from the CLEWS approach, it possesses some

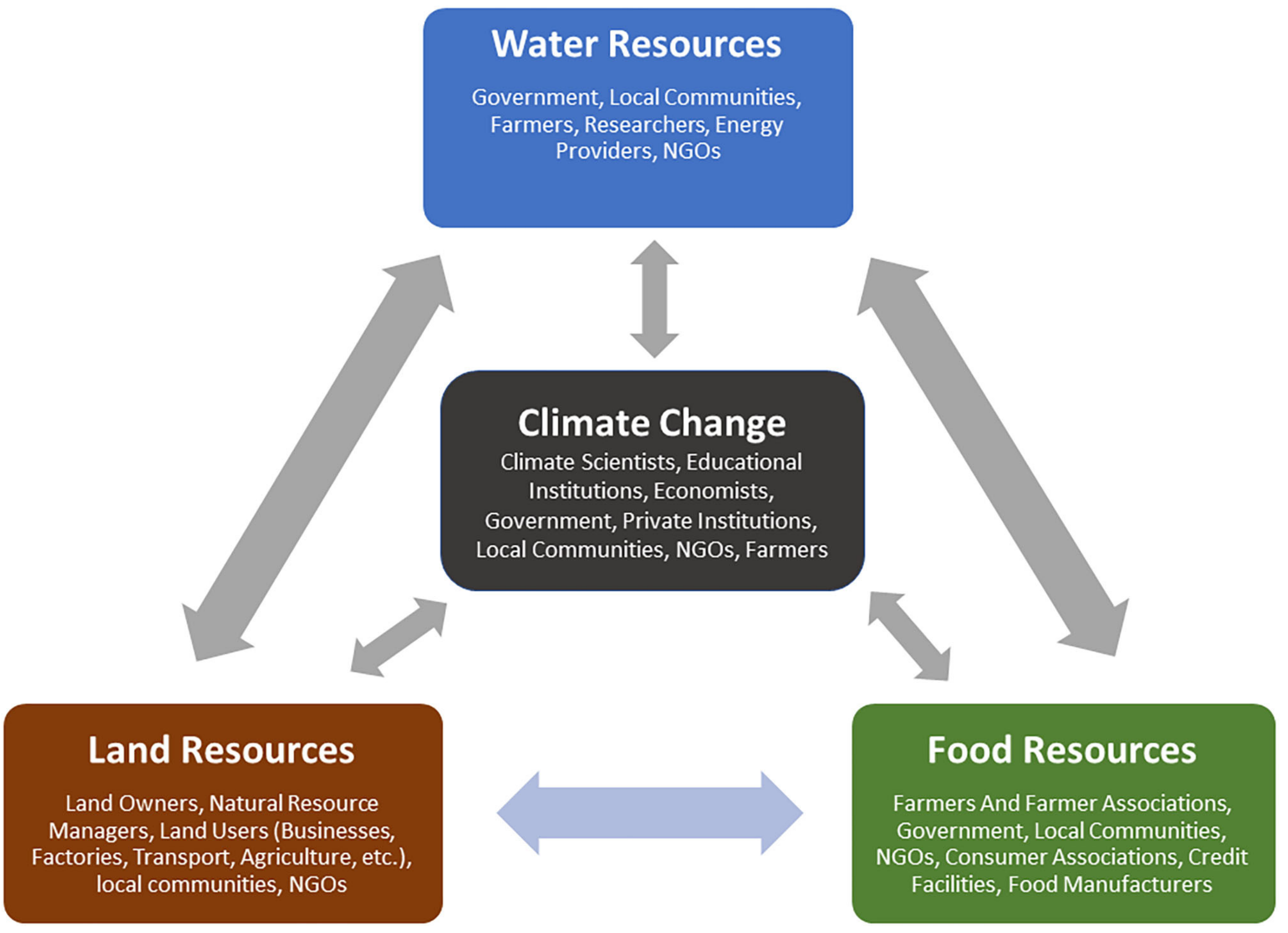

FIGURE 1 | A flowchart representing the climate change and WLF security nexus and the key stakeholders involved in the policymaking process.

limitations. It is only able to promote more interactions between the components of the nexus when used at a larger scale (regional and national level studies). At smaller scales (local level studies), the interactions between the components of the nexus appear to be limited and rather promotes intra-linkages between them. Moreover, mechanisms are not available to promote the transfer of methods and approaches across the regional, national, and/or local scales (Ramos et al., 2021).

To achieve the WLF security nexus in a changing climate, sufficient attention must be given to both national and international organizations/institutions in SSA. They must be able to integrate the outcomes WLF security nexus generated from the multidisciplinary teams into adaptation and mitigation plans toward climate change. Considering the novelty of the WLF security nexus approach in the policymaking process of SSA region, efforts must be taken to deepen the knowledge hub of the stakeholders which will help to foster the ease of interactions between them. Finally, governments and private institutions must be ready to invest or provide institutional support to attract investments for promoting the WLF security nexus (Rasul and Sharma, 2016).

AUTHOR CONTRIBUTIONS

SAO: writing and editing of manuscript. SC and SO: editing and review of manuscript. All authors contributed to the article and approved the submitted version.

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Environmental Services: A New Approach Toward Addressing Sustainable Development Goals in Sub-Saharan Africa

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The physical environment provides resources and specific types of environmental services relevant to the maintenance of human livelihoods globally and with specific reference to sub-Saharan Africa, including soils, food, and water systems. Previous studies on the shared nexus of such resources commonly view these as self-contained systems operating independent of their physical contexts provided by landscape-scale geomorphology and its related processes. This study critically examines the viewpoints adopted by such nexus studies with specific reference to sub-Saharan Africa, arguing that these studies are reductive, considering only the shared disciplinary overlap (nexus) and not their wider contexts, and are based on only a limited understanding of the workings of physical systems. This study argues that considering the attributes of the physical landscape and its provision of environmental services provides a broader and scientifically-informed context for understanding of interlinked issues such as relationships between soil–food–water systems. Framing such "nexus" studies in this wider context can derive a better understanding of the connections between different elements such as soil, food, and water, amongst others, and with respect to the United Nations' Sustainable Development Goals. The concept of environmental services is therefore a more powerful tool to examine both the connections between physical and human environmental processes and properties in sub-Saharan Africa, and to address overarching environmental issues such as land degradation, soil erosion loss, water scarcity, and impacts of climate change.

Keywords: environmental resources, sustainable development goals, ecosystem services, nexus, landscape development, sustainability, Sub-Saharan Africa

INTRODUCTION

The physical landscape is the basis for the provision of different types of environmental resources (O'Farrell et al., 2010; Thondhlana and Muchapondwa, 2014; Falayi et al., 2019; Ragie et al., 2020). Environmental resources can be defined as any properties or attributes of the physical environment, including its climate, that provide direct or indirect services of different types to local communities. Environmental resources can therefore be considered as related to, but broader than, ideas of ecosystem services (van Jaarsveld et al., 2005; King-Okumu, 2018). For this reason, the concept of *environmental* *resources* and the services that they provide (termed *environmental services*) is a more useful and integrated approach that is founded on ideas of Earth System Science that describe the interlinkage of changes that take place in the physical environment (Clifford and Richards, 2005). Consideration of environmental services, through the provision of different types of environmental resources, is of relevance to studies of physical–human relations in sub-Saharan Africa where issues of environmental sustainability are important (e.g., Hoffman et al., 2007; O'Farrell et al., 2010; Vogel et al., 2016), as are expressed in the United Nations' Sustainable Development Goals (SDGs) (Millennium Ecosystems Assessment, 2005). Several studies have examined how communities make use of environmental resources in their immediate localities, illustrating the local-scale relationships of people to their surrounding environments (e.g., Hoffman et al., 2007; Casale et al., 2010; Thondhlana and Muchapondwa, 2014; Cole et al., 2017; Omisore, 2018; Falayi et al., 2019; Ragie et al., 2020). These relationships have often been examined in the context of resource sustainability, by which the use of certain environmental resources is evaluated over time with respect to changes in resource properties and their availability (e.g., Hallowes et al., 2008; Swemmer et al., 2019; Wolff et al., 2019). However, this analysis of relationships between different communities and environmental resources is usually based on localized and individual case studies. What is critically lacking is an evidence-based theoretical context in which to link different case studies together, to aid their interpretation, and as an overarching framework for evidence-based decision-making.

Many previous studies have described the relations between different elements in physical and human environments with respect to their shared *nexus* (**Figure 1**). This term, which is not well-described although commonly used in the literature, refers the thematic interconnection or area of overlap between two or more elements of the human and/or physical environments. As such, the shared nexus between these different elements is a qualitative and poorly defined space that is dependent on the capacity of individual researchers to make intellectual links between these elements. Thus, nexus studies do not always provide an adequate intellectual foundation for either designing or interpreting field-based studies, or in applying an understanding of these co-relationships to solve a practical problems, such as soil erosion or declining agricultural yields. This means that many nexus studies, while purporting to be integrative and based on ideas in sustainability, cannot be readily applied to address SDGs.

Several different examples of nexus studies in sub-Saharan Africa have been reported in the literature (**Table 1**). *Energy*, *water*, and *food* are the most common elements considered in these studies, either together or in combination with other elements. The majority of nexus studies provide local examples of physical–human relationships; only few studies have examined the links between physical–human nexuses to broader aspects of sustainability and the SDGs. For example, Ramutsindela (2003), Wolff et al. (2019) and Musakwa et al. (2020a) described land-use management implications of the physical–human nexus with specific reference to urbanization, land reform and tenure, and their relationships to nature and biodiversity conservation.

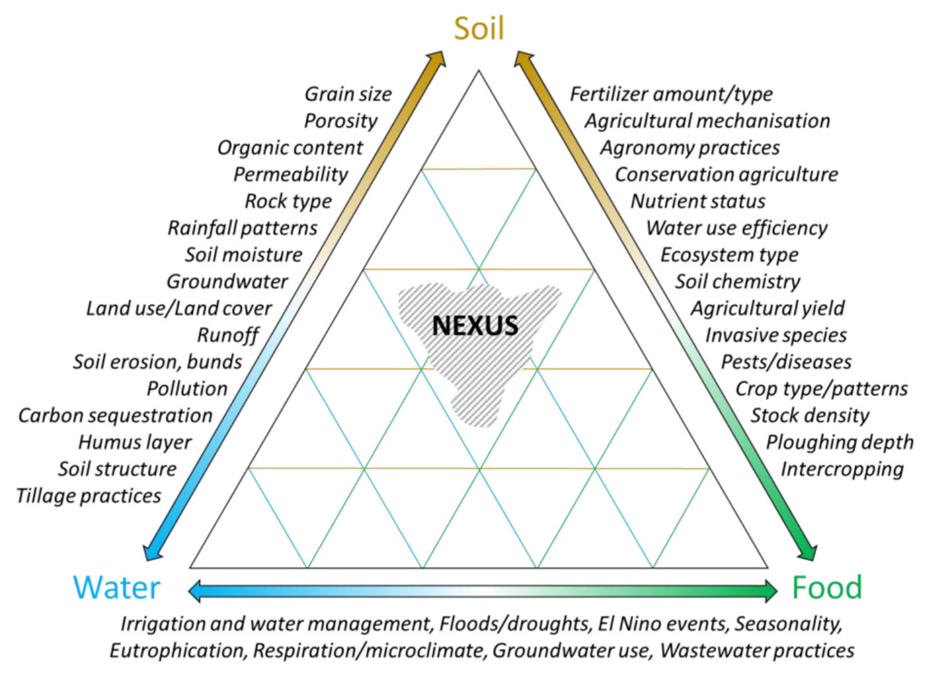

FIGURE 1 | Illustration of the interconnections between soil, food, and water systems and the particular elements that link these systems together (listed around the outside of the triangle). The soil–food–water nexus represents some poorly-defined region in the middle of this triangle (shaded).

TABLE 1 | Examples of nexus studies in South Africa.

Nexus type	Examples described in the literature (source)
Agriculture–population	Alola and Alola, 2019
Energy–climate	Bazilian et al., 2011
Urban–rural	Constant and Taylor, 2020
Urbanization–food security	Jonah and May, 2020
Energy–water	Hoseini et al., 2016; Ololade, 2018
Land–water	Marcatelli, 2018; Rosa et al., 2019
Environment–trade	Udeagha and Ngepah, 2019
Growth–poverty–inequality	Akanbi, 2016
Energy–climate–economic growth	Cowan et al., 2014; Akadiri et al., 2019; Azam, 2019; Bekun et al., 2019; Khan et al., 2020
Biodiversity–poverty–inequality	Graham and Ernstson, 2012
Energy–pollution–*growth*	Magazzino et al., 2020
Energy–water–CO_2	Madolo et al., 2018
Energy–water–waste	Wang et al., 2018
Food–energy–water	Ozturk, 2017; Zaman et al., 2017; Mabhaudhi et al., 2018, 2019; Mpandeli et al., 2018; Zhang et al., 2018; Sahle et al., 2019; Simpson et al., 2019; Nhamo et al., 2020a,b; Bellezoni et al., 2021; Yuan et al., 2021
Water–energy–food–climate	King and Jaafar, 2015

Items of these nexuses that are specifically mentioned in the United Nations' Sustainable Development Goals are listed in italics.

Several studies have also considered the relationship of water management to sustainable development (Jonker, 2007; Mabhaudhi et al., 2018, 2019; Nhemachena et al., 2020) but this is viewed mainly as a water budget (supply/demand) issue rather than as a system that links synergistically to other systems (soil, ecosystems, agriculture, health, pollution).

Despite the fact that most nexus studies have a clear—albeit unstated—application to SDGs (marked in **Table 1**), and can be applied to a range of cross-cutting physical–human environmental issues, these studies are rarely framed in a context of either sustainable development (e.g., Walmsley, 2002; Hoffman et al., 2007; Nhemachena et al., 2020) or Earth System Science that informs on co-relationships to physical processes in the landscape (Knight, 2015; Verburg et al., 2015). This is a key limitation of nexus studies because it means they are not informed by the physical and human environmental processes that impact on issues in sustainability and the SDGs. Nexus studies, by definition, are reductive because they consider co-relationships of different elements (food, water, energy, etc) through a very narrow and exclusionary lens. They consider these different elements as distinct and mutually exclusive with respect to their properties or dynamics or controls, except for some specific areas of thematic overlap (their *nexus*).

This paper tackles this systemic weakness of nexus studies by proposing a new, holistic and integrated framework that examines the application of *environmental services* and their associated *environmental resources* to address the aspirations of the SDGs. These related elements are explored through the commonly-examined "nexus" of soil–food–water systems as has been widely discussed in the literature in sub-Saharan Africa (**Figure 1**). This paper (1) examines the nature of this nexus, drawing from previous studies in the literature; (2) reframes this nexus using ideas of environmental systems, their resources and services; (3) discusses the nexus of soil–food–water systems using a specific example of smallholder farmer practices in Limpopo Province, South Africa; and (4) provides a new way of examining co-relationships between soil, food, and water through the concept of *cascading environmental systems*. A critical outcome of this study is an evidence-based theoretical context of physical and human systems relevant to SDGs, and issues of sustainability and sustainable development more generally, and especially in a sub-Saharan Africa context.

THE SOIL–FOOD–WATER NEXUS

The flow of energy and matter through landscapes is controlled by topography and is driven by biophysical processes and water flow. Soil, food, and water systems thus have very different relationships to the physical environment: water relates strongly to climate, soil to geology, and "food" merely represents the acquisition and commodifying of biological resources by human activity. "Food" is therefore a value-laden concept, being a subset of ecosystem services, and is mediated by socioeconomic and cultural attributes of different regions, people, and contexts. This means that soil, food, and water are not of equal or comparable status within a single "nexus," even though studies that address these elements within a single nexus assume that they are. Soil (land surface), food, and water systems in sub-Saharan Africa have been examined in several nexus studies and with respect to the nature of the relationships between these elements as viewed from different perspectives (e.g., decision-making, climate change adaptation, land degradation, regional economic development, sustainable water management, etc) (Mpandeli et al., 2018; Nhamo et al., 2020a,b). This means that such nexus studies take different disciplinary viewpoints, and in emphasizing certain of these elements, can result in only a partial understanding of these interrelationships. **Figure 1** outlines the detailed nature of interactions between soil, food, and water systems. Each axis describes the relationships between these different elements. It is notable that no nexus study, presented in the literature, has examined these elements in detail or described the theoretical basis of these relationships. The co-relationships between soil, food, and water (shown in **Figure 1**), however, are now examined in detail.

Soil and water systems focus on how the physical and chemical properties of soil influence water retention and throughflow properties and processes. Specific controls on soil and water system properties include aspects of climate (rainfall patterns, runoff, soil erosion), geology (rock type, grain size, porosity, permeability, groundwater position, and dynamics), soil properties (grain size, organic content, soil structure, soil moisture capacity), vegetation (land use, agriculture type, humus/nutrient content), and management structures (field bunds, tillage practice). Relationships between these different elements have been discussed in several studies. For example, soil properties such as carbon content have been explicitly linked to minimal tillage conservation agriculture methods (e.g., Willcocks and Twomlow, 1993; Bationo et al., 2007; Mchunu et al., 2011; Simwaka et al., 2020). Here, conservation agriculture techniques give rise to changes in soil and water properties, with an increase in porosity resulting in an increased capacity for soil moisture storage, increase in soil carbon stock, and changes in particle size distributions within soils. Water processes within the soil are associated with chemical translocation, which is of particular relevance for nutrients and soil fertility (Smaling et al., 1993; Mabuza and van Huyssteen, 2019; Teffera et al., 2019). Studies have also been concerned with rainwater harvesting and its effects on soil moisture retention (van Rensburg et al., 2012). *Soil and food systems* describe ecosystem type and productivity that relates to soil nutrient status and the agronomy practices that affect soil properties. Soil and food systems therefore include aspects of soil management (fertilizers, nutrient status, plow depth), crop type, and agricultural practices (agronomy practices, intercropping, harvesting, and land management practices), and agricultural ecosystem management (invasive species, pests/diseases). Balancing soil nutrient status and plant growth requirements is a key component of integrated soil and food systems. Studies that consider these systems therefore focus on how different cropping systems or stock density affect soil properties. Examples include the role of beans and other staple crops in soil nitrogen fixation (Mthembu et al., 2018; Muoni et al., 2019; Namatsheve et al., 2020), micronutrient provision within soils as a result of specific crop types and practices (Nziguheba et al., 2016; Kihara et al., 2020a), relationships between agricultural yield and soil fertility (Tan et al., 2005; Lal, 2009; Soropa et al., 2019), the role of additions of fertilizer and manure in food production (Vlek, 1990; Mafongoya et al., 2006), the relationship of soils to ecosystems and biodiversity in agricultural systems (Agegnehu and Amede, 2017; Kamau et al., 2019; Kihara et al., 2020b), and the role of different agronomy practices such as intercropping and livestock/arable combinations on soil fertility and agricultural yield (Gowing et al., 2020; Hoffmann et al., 2020; Reetsch et al., 2020). These studies on soil and food systems highlight the critical role of human activity in changing the nature of the land surface (vegetation, soil A-horizon, input of water/fertilizer) that then has impacts on soil properties. Further, maintenance of soil properties (structure, thickness, organic and moisture content, nutrient status) is the basis for sustainable food production (Vlek, 1990; Lal, 2009; Bindraban et al., 2012; Graef et al., 2015; Solomon et al., 2016). Interrelationships of *food and water* systems are based on the different water requirements for different crops or agricultural systems, managing water for irrigation during dry periods, and managing the effects of excess and wastewater during wet periods. Water use efficiency with respect to food production are explicitly linked to sustainability and with reference to SDG 2 (food security) (Wallace and Gregory, 2002; Cook et al., 2009; Nyam et al., 2020). Studies on food and water systems have focused on water use efficiency with respect to specific crops (Makurira et al., 2011; Nyakudya and Stroosnijder, 2011; Olivier and Singels, 2015), rainwater harvesting (Botha et al., 2012; Baiyegunhi, 2015; Mo et al., 2018), and rainfed agricultural systems (Mutiro et al., 2006; Biazin et al., 2012; Haarhoff et al., 2020). These studies show the key role of water availability and management in influencing food production systems. Water management is also influenced by crop type and mulch cover, which can reduce evaporation and increase soil moisture retention by up to 30% (Biazin et al., 2012; Olivier and Singels, 2015). Studies have also shown that effective water management can lead to increased yields and higher gross margins (Makurira et al., 2011; Sime et al., 2015).

Apart from individual shared elements that link up individual soil, food, and water systems (**Figure 1**), several studies have also examined this soil–food–water nexus in the context of sustainable development. For example, Love et al. (2006) and Kadyampakeni (2014) argued that SDG 2 (food security) can be addressed through increased access to fertilizers, technology transfer and training, soil-water conservation methods, mixed livestock and arable agriculture, and farm diversification. It is notable that each of these proposed interventions involves co-relationships between different elements of physical and human systems, and that these relationships are not straightforward or without impact. As an example, increased access to fertilizer as a simple action point requires input from or influence by a range of actors, processes and properties, and in turn fertilizer input impacts upon a range of issues related to the physical environment, farm properties, and wider socioeconomic systems (**Figure 2**). Thus, addressing this action point requires a fuller consideration of systems' properties, which is not usually done in nexus studies. Further, this highlights the problems of enacting seemingly-simple management decisions when also set against such naïve and poorly-defined statements as "end hunger, achieve food security" of SDG 2, for example. This means that many nexus studies only describe broad and generalized relationships with respect to SDGs (Ololade, 2018; Zhang et al., 2018; Simpson et al., 2019), and lack specific and evidence-based scientific detail that is set in a theoretical context (Graham and Ernstson, 2012). To address this, the theoretical context of *environmental services* is now proposed as a way to better understand the co-relationships of different physical and human elements, as described in nexus studies.

ENVIRONMENTAL SERVICES AS A BASIS FOR UNDERSTANDING OF SOIL, FOOD, AND WATER SYSTEMS

The Nature of Ecological Environmental Services

Ecosystem services are well-known and documented especially in a southern African context (van Jaarsveld et al., 2005; Egoh et al., 2008; Fenta et al., 2020; Mowat and Rhodes, 2020) and these are linked directly to human–environment (socio-ecological) relationships and aspects of sustainable development (Bailey and Buck, 2016; Sigwela et al., 2017; Cerretelli et al., 2018; Bengochea Paz et al., 2020). Many local case studies worldwide have described different ecosystem

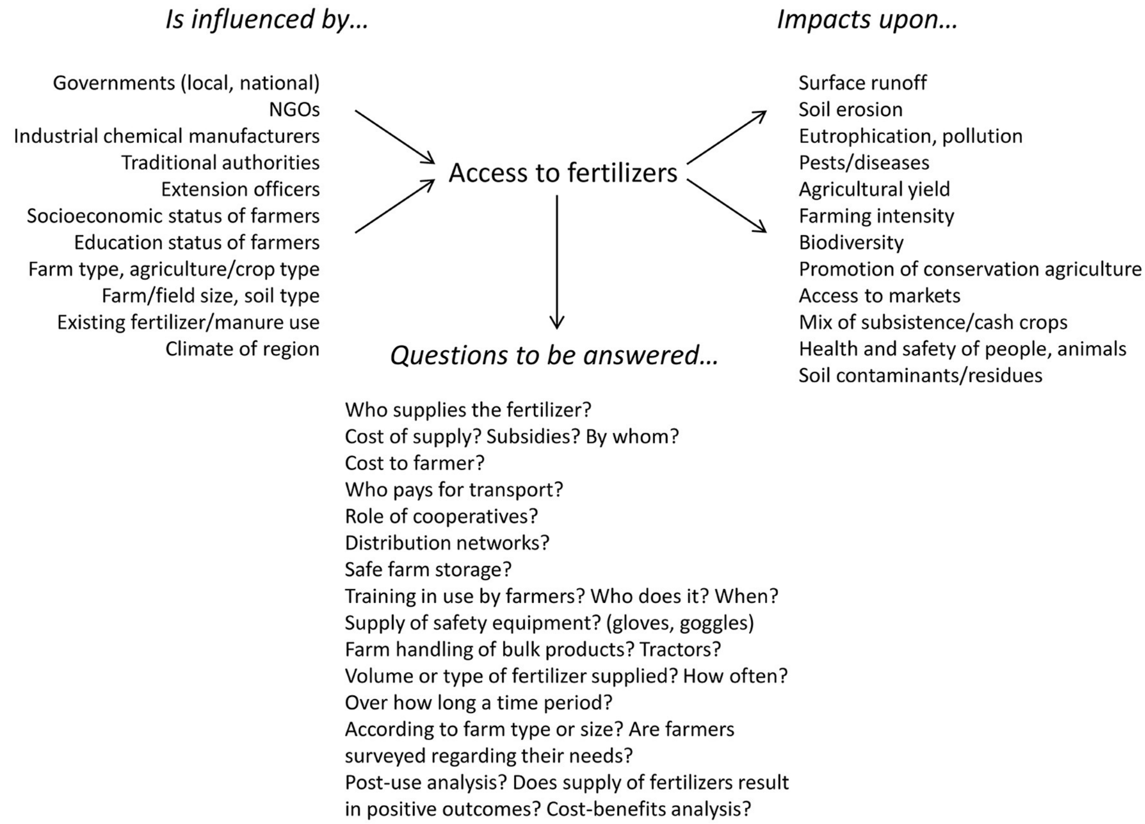

FIGURE 2 | Example of how a simple intervention such as access to fertilizer (Love et al., 2006) links to wider aspects of nexus intersections in the physical and human environments.

services and their uses by communities in different, mainly agricultural, contexts (e.g., Mensah et al., 2017; Swemmer et al., 2019; Herd-Hoare and Shackleton, 2020; Lhoest et al., 2020). The conceptual basis for understanding these ecosystem services is well-founded because it is based on ecological processes set in a landscape context, and studies of ecosystem services are framed by well-defined theoretical approaches, which include:

- Socio-ecological approaches that consider human use and ecological resources as part of a continuum (e.g., Temesgen and Wu, 2018; Bengochea Paz et al., 2020);
- Monitoring and modeling of variations in aboveground productivity using remote sensing tools such as normalized difference vegetation index (NDVI) values (e.g., Lindeskog et al., 2013; Ayanlade and Proske, 2016; Cho and Ramoelo, 2019);
- Valorizing ecosystem services based on calculations of ecosystem use and areal coverage of different ecosystem types (e.g., Costanza et al., 2011; Anderson et al., 2017; Turpie et al., 2017; Niquisse and Cabral, 2018);
- Interpreting different service types and provision through ideas of natural capital (e.g., Costanza and Daly, 1992; Blignaut and van der Elst, 2014); and
- Payment for ecosystem services (PES) (e.g., Jackson and Palmer, 2015; Haile et al., 2019).

However, these different approaches adopted in studies of ecosystem services do not explicitly consider how ecosystems influence environmental variables such as geomorphology, soils, water availability (rivers, groundwater) and climate, or how local communities may use or value these properties and services. Despite this importance, only a few studies on ecosystem services are set in a broader environmental context (e.g., Egoh et al., 2009; Pettinotti et al., 2018; Balbi et al., 2019). This omission is surprising given the wide literature on the relationship of ecosystem service provision to land degradation (e.g., Smiraglia et al., 2016; Sutton et al., 2016; Tarrasón et al., 2016; Turner et al., 2016; Cerretelli et al., 2018). In addition, environmental services, provided by or contingent upon the physical landscape, have not been explicitly considered as part of sustainable development strategies in developing world contexts, or as key elements of SDGs, despite the plethora of "nexus" approaches that are linked to examination of the SDGs (Cumming et al., 2017; Nhamo, 2017; Omisore, 2018; Dawson et al., 2019; Jiménez-Aceituno et al., 2020; Nhemachena et al., 2020).

Based on this discussion, it is evident that there are limitations of ecosystem services alone to apply to the wide range of

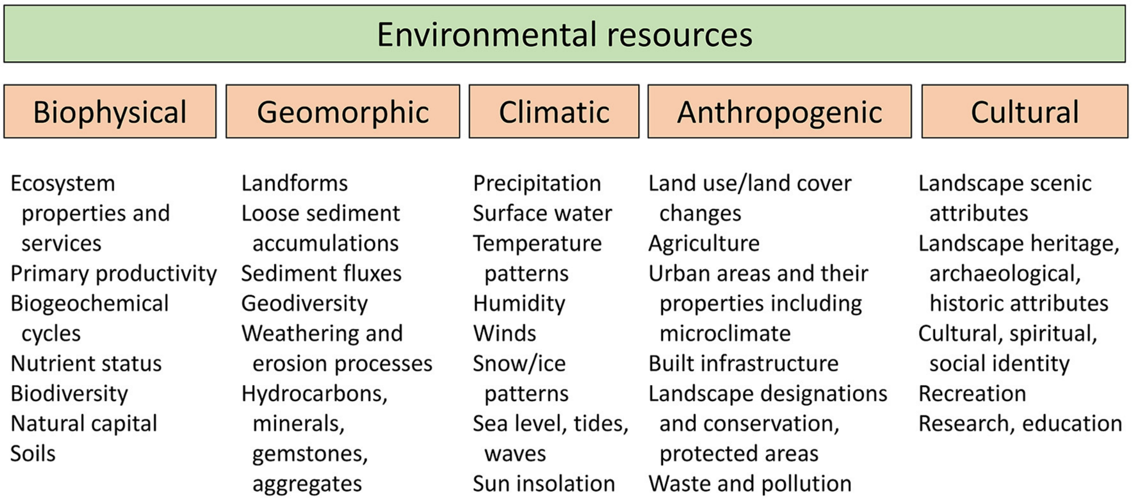

FIGURE 3 | Illustration of different types of environmental resources [informed by Gray (2004), Millennium Ecosystems Assessment (2005)]. Note that ecosystem resources and services are a subset of broader environmental resources and services.

environmental factors that give rise to changes in the physical or human environments, or to describe their interconnections. This does not mean that ecosystem service approaches are not useful either on their own merit or in addressing the SDGs, but merely that they do not explicitly consider wider environmental factors as contributors to ecosystem processes and therefore service provision. For this reason, landscape-scale environmental factors (e.g., geology, geomorphology, soils, water, climate) can be considered as *environmental resources* that are potentially available for use by other Earth systems and by human activity (**Figure 3**). In so doing, these environmental resources then provide a range of *environmental services*. This approach therefore views human activity and human intervention in Earth systems as a key component in the provision and use of environmental resources on a global scale (e.g., Knight and Harrison, 2014; Knight, 2015), therefore that environmental resources and human activity are intimately related (**Figure 4**). This contrasts with many studies that view ecosystem services as some fixed, pre-existing and inherent entity of the physical environment that is separate from human activity and the human world, and that human activity seeks only to draw from ecosystem services rather than interact with it (e.g., Chaigneau et al., 2019; Lhoest et al., 2020). In the Anthropocene, several studies show that environmental resources (*sensu lato*) are vulnerable as a result of human activity and climate change in combination (Knight, 2015; Bradshaw et al., 2021), which sets the scene for their more careful examination with respect to achieving future developmental benchmarks such as the SDGs. Environmental resources can be classified into biophysical, geomorphic, climatic, anthropogenic, and cultural resources types (**Figure 3**). Relationships between these take place along a continuum between those resources that are wholly related to the physical environment, and those that are wholly related to the human environment (**Figure 4**). The applicability of an environmental resources and services approach to examining

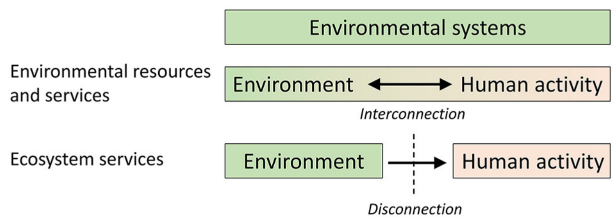

FIGURE 4 | Illustration of how environmental resources and services link together aspects of the physical environment and human activity, in contrast to many studies of ecosystem services.

soil, food, and water systems is now presented. The purpose of this more detailed analysis is to highlight how an environmental service approach is more useful and integrative, compared to a reductive nexus approach.

Environmental Services and Soil, Food, and Water Systems

Soil, food, and water systems can not only be conceptually related to each other (cf. nexus studies; **Figure 1**) but also to other environmental systems. As such, a reductive nexus approach does not describe the interrelations between individual elements and their wider environmental contexts. **Figure 5** builds from **Figure 1** by taking all the integrated factors that link soil, food, and water systems together and grouping them according to their major controls. These different factors are color coded according to whether they broadly correspond to soil, food, or water systems. This shows that environmental services provided by soil, food, or water systems are influenced by a range of different factors (**Figure 5**). Further, individual elements can also be considered as providing environmental services to other elements, which highlights the intersectionality between

Ecological and land use factors
Land use/land cover
Eutrophication
Ecosystem type
Invasive species
Agricultural yield

Agronomy factors
Bunds
Tillage practices
Agricultural mechanisation
Conservation agriculture
Water use efficiency
Crop type/patterns
Ploughing depth
Intercropping
Groundwater use

Edaphic factors
Grain size
Porosity
Organic content
Permeability
Soil moisture
Carbon sequestration
Humus layer
Soil structure
Nutrient status
Soil chemistry

Geological factors
Rock type
Groundwater
Runoff

Socioeconomic and management factors
Pollution
Fertilizer amount/type
Pests/diseases
Stock density
Irrigation/water management
Wastewater practices

Climatic factors
Rainfall patterns
Soil erosion
Floods/droughts
El Nino events
Seasonality
Respiration/microclimate

FIGURE 5 | Grouping of different factors that link soil, food, and water systems together (**Figure 1**) according to their major controls. The different factors are color coded according to whether they correspond to soil (brown), food (green), or water (blue, following **Figure 1**).

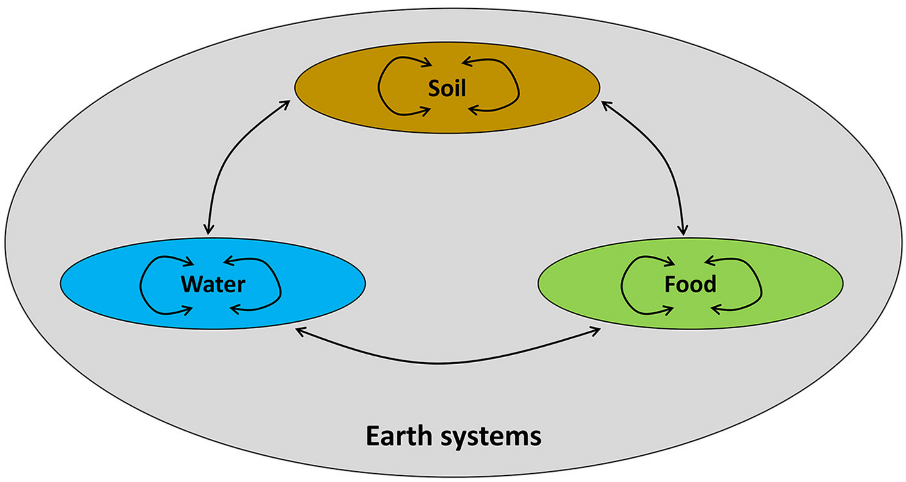

FIGURE 6 | The nature of cascading systems as applied to soil-food-water systems examined in this study.

environmental resources, their services, and commodification of these elements by local communities. Here it is argued that a useful conceptual framework for understanding the interconnections between these different elements is that of a *cascading system*, in which there are active feedbacks between different elements that are driven by flows of energy and matter. These cascading systems and their applications to the environment are now examined.

Cascading Environmental Systems

The concept of cascading systems refers to how information and energy is dispersed (cascaded) amongst the constituent elements of a network, within and between each system and subsystem (**Figure 6**). A key property of cascading systems is that, through feedback processes, dynamic equilibrium of the system as a whole can be maintained (Pratt and Eslinger, 1997). This conforms with the workings of feedbacks in Earth Systems (Clifford and Richards, 2005). Cascading systems are best considered as "bottom-up" systems subject to self-organization, in which the nature of their network relations (network topology) emerge over time as energy and matter flow through the system (Pratt and Eslinger, 1997; Gleeson and Durrett, 2017). These are non-dimensional systems and thus do not correspond to any specific spatial or temporal scales (Gleeson and Durrett, 2017) but are subject to system perturbations that have impacts on system dynamics, including non-linear and lagged forcing–response relations (Young et al., 2017). These properties of cascading systems match well with the ways in which physical processes of weathering, erosion and ecosystem changes are experienced in the landscape, which can also be considered to operate under non-dimensional boundary conditions (e.g., Molden and Bos, 2005).

The cascading nature of integrated soil–food–water systems is now examined, and this takes place in the wider context of Earth Systems in which there are feedbacks within and between each of these different elements (**Figure 6**), and where both physical and human environmental factors are involved (**Figure 1**). Climate forcing of weathering and erosion processes at a landscape scale (Dixon et al., 2009) gives rise to the generation of loose surface materials that transform into soil by development of surface vegetation. By processes of negative feedback, bedrock weathering rates decrease over time and this is accompanied by a decrease in slope angle as progressive soil creep driven by gravity takes place (Phillips, 2005). This gives rise to enhanced slope sediment yield and therefore the net transfer of soil volume from upper/midslope locations to mid/footslope locations (**Figure 7**). Likewise, there are also feedbacks between soil properties, runoff and surface ecosystems, and these include hydrological (interception, root system uptake, surface desiccation) and mechanical processes (anchoring processes that increase soil strength and reduce erosivity) (Marston, 2010). Soil erosion is enhanced under agricultural land uses where the natural vegetation cover is replaced by sown crops of different types that leave the soil surface bare after harvest, and where changes in soil structure and chemistry take place by deep tillage and addition of fertilizer (Vanwalleghem et al., 2017). Geological background erosion rates on soil-mantled slopes is on the order of 0.001–1 mm yr^{-1} whereas under agriculture of different types this is increased to 0.1–80 mm yr^{-1} (Montgomery, 2007). Enhanced soil erosion is therefore associated with a decrease in agricultural yield (Montgomery, 2007; Vanwalleghem et al., 2017). However, this is set against the concept of soil loss tolerance, in which soil erosion operates until such a time as when agricultural yields are negatively affected, prompting a management response (Li et al., 2009). Thus, the relationship between soil and food systems is influenced by feedbacks that also includes the human environment, set within the context of Earth systems (**Figure 6**).

There is a positive relationship ($r = 0.592$) between soil erosion loss and 30-min breakpoint rain intensity (EI_{30}) (Kinnell, 2010), and this relationship has been used for predicting spatial patterns of soil erosion loss in Africa under climate change (Diodato et al., 2013). Studies have also identified that ecological responses to climate change lead to changes in agricultural productivity (Higgins et al., 2002). These reflect temperature and precipitation changes as forcing factors for phenological and primary productivity responses (e.g., Anderson et al., 2015; Porkka et al., 2016) but these factors also affect soil chemistry, nutrients, and carbon storage (Quinton et al., 2010), and it is this that eventually affects outcomes of food security (Kang et al., 2009; Sonwa et al., 2017). Jägermeyr et al. (2016) suggested that more efficient water use can increase kcal-equivalent production by 26% globally, corresponding to increased volumetric global food production by 41%. This highlights the co-relations between soil, food, and water systems (**Figure 6**) and that this understanding can be applied to SDGs (Charlton, 2016; Nhemachena et al., 2018; Newell et al., 2019).

FIGURE 7 | Example of soil erosion on an agricultural field, showing midslope erosional gullies and soil deposition at the footslope (bottom of the image).

Case Study: the Example of Soil–Food–Water Systems in Limpopo, South Africa

Limpopo Province in northeast South Africa is a rural and semiarid region (mean annual rainfall of 598 mm) where there are more than 4 million smallholder and subsistence farmers (Aliber and Hart, 2009). Farming is therefore a key livelihood strategy and important for food security and nutrition (van Averbeke and Khosa, 2007; Aliber and Hart, 2009; Musakwa et al., 2020b). Products include both staple crops for consumption (maize, butternut, cabbage, beans) and vegetable market crops for sale (spinach, lettuce, tomatoes, carrots, onions) (Bharwani et al., 2005; Mahlangu et al., 2020; Musakwa et al., 2020b) (**Figure 8**). Soil types in the region, within the Limpopo River catchment, are mainly sandy loam luvisols that are favorable for agriculture but which require additional fertilizer (Molepo et al., 2017). Techniques used include the application of manure and compost, crop rotation and intercropping, and farmers are explicitly aware of the ability of these methods to increase soil nutrients and reduce erosion loss (Rusere et al., 2020). Water management is also a key issue in this area and experimental studies have shown that agricultural yields on sandy loam soils can be increased by up to 20% with effective water management (Magombeyi et al., 2018), and this can also increase vitamin availability at the household level (van Averbeke and Khosa, 2007). Most (60%) of surveyed smallholder farmers in central Limpopo report challenges in accessing water, mainly through groundwater boreholes (Chikozho et al., 2020). There may also be inadequate rainwater storage facilities (e.g., **Figure 8D**), competition for water between users, loss of water by infiltration, damage to

FIGURE 8 | Examples of agricultural activities in Limpopo Province, South Africa. **(A)** Agricultural fields at Mamotintane, where the total farm size is 9 ha with scattered rectangular farm plots for individual smallholder farmers. **(B)** A community-shared field (1 ha) at Segoptje. **(C)** A field 4 ha in size at Sickline with rectangular farm plots. **(D)** Irrigation system used for watering crops during the dry season (photos: Rirhandu Chauke).

canals and furrows, and general increased aridity (Kativhu et al., 2020).

Analysis of the challenges faced by smallholder farmers in Limpopo shows that aspects of both soil, food, and water systems are important, and that these are linked together in several different ways (Radosavljevic et al., 2020; Rusere et al., 2020). For example, food insecurity arises as a combination of lack of education, job opportunities, mobility, health, demographic factors, and other socioeconomic factors (Oni et al., 2010; Ramos-Mejía et al., 2018). Smallholder farming is therefore a life support strategy for more than just the provision of food resources, being linked explicitly to SDGs 1, 2, 3, 11, 12, 13, 15 (see https://sdgs.un.org/goals) (e.g., Dawson et al., 2019; Newell et al., 2019). The success of smallholder farmer activity in Limpopo has also been critically linked to the presence and nature of government support mechanisms, including social grants, training, and agricultural extension (Kativhu et al., 2020). Some smallholder farmers may also be part of cooperatives and this can help in marketing of products, sharing of seeds and expertise, and can increase resilience (Bharwani et al., 2005; Aliber and Hart, 2009; Mahlangu et al., 2020). This example from Limpopo Province shows the interconnected nature of environmental systems and services, and the important strategic role of governance and management institutions in contributing toward the success of soil, food, and water systems in the context of sustainable development.

DISCUSSION

Understanding the relationships between soil, food, and water systems is fundamental to addressing the SDGs in the context of ensuring food and water security in the developing world. Most previous studies, in particular those that take a nexus approach, have a limited and reductive focus because they only consider the narrow interconnections between soil, food, and water, and not the wider environmental contexts that help frame these interconnections (**Figure 1**). These interconnections are well-demonstrated in Limpopo Province where the activities of smallholder farmers are taken in response to the nature of soil, water, and nutrient requirements for their crops, but which are also affected by wider socioeconomic factors of the marketplace and by certain government interventions. Consideration of environmental services (e.g., Jonker, 2007; Pettinotti et al., 2018) is a useful approach toward addressing the multiple stressors that lead to societal vulnerabilities in sub-Saharan Africa (Casale et al., 2010; Vogel et al., 2016; Falayi et al., 2019). Several studies have identified the correspondence between SDGs and aspects of the environment (*sensu lato*), including climate and ecosystems (e.g., Walmsley, 2002; Cumming et al., 2017; Nhamo, 2017; Omisore, 2018; Dawson et al., 2019) but this recognition has not followed through into meaningful developmental strategies that use environmental measures as performance indicators (Nhemachena et al., 2018; Le Roux and Pretorius, 2019; Jiménez-Aceituno et al., 2020). There is therefore a disconnection between the driving factors behind sustainable development, and the performance indicators used for monitoring achievement of SDGs (e.g., Patole, 2018; Schipper et al., 2021). This is clearly an issue for correctly identifying, enacting and monitoring the success of sustainable development strategies (Knight, 2015).

Management of environmental resources (**Figure 3**) is commonly framed in terms of sustainable development (Hallowes et al., 2008; Cumming et al., 2017; Falayi et al., 2019; Wolff et al., 2019), but an alternative viewpoint is where socioecological processes between people and the environment are also considered (e.g., Bowd et al., 2015; Ramos-Mejía et al., 2018; Fedele et al., 2020; Herrfahrdt-Pähle et al., 2020). Here, human activity can be viewed as either an integrated element of the Earth system and synergistically influencing ecological processes and ecosystem services through feedback processes (Swemmer et al., 2019; Musakwa et al., 2020a; Ragie et al., 2020), or as an external driver of irreversible environmental change and degradation (D'Alessandro and Zulu, 2017; Schmiedel et al., 2017; Ashukem, 2020). Balancing these different perspectives is necessary for a more scientifically-grounded and evidence-supported basis for (1) understanding of environmental issues (*sensu lato*) and their contexts in the developing world and specifically sub-Saharan Africa; (2) developing appropriate tools for engaging with communities and other stakeholders on environmental and sociocultural issues; (3) developing long-term strategies that converge on achieving both specific SDGs and recognizing the intersectionality of all SDGs with respect to the natural environment and human communities; and (4) identifying appropriate and multidimensional performance indicators that can be used consistently and objectively to describe the nature of environmental change, changes in environmental resources and their services, and considering the functionality of Earth and environmental systems that deliver these resources and services in different ways. The concept of cascading environmental systems, in which there are feedbacks between and within different components within systems, provides a more useful framework for describing and interpreting their co-relationships (**Figure 6**). These relationships can also better describe interconnections to the human environment and how environmental resources and services are commodified and used by individuals and communities.

CONCLUSIONS AND FUTURE RESEARCH OUTLOOKS

Environmental resources and services provide the means to fulfill the SDGs but the nature and dynamics of these resources and services are still not well-known, in particular in sub-Saharan Africa where food and water insecurity are significant developmental issues (Casale et al., 2010; Omisore, 2018; Dawson et al., 2019). It is notable that previous studies taking a nexus approach to different issues including food, water, energy, waste, climate, land, and economic growth do not explore the detailed interconnections between these elements, or use the powerful interpretive framework of Earth Systems (**Table 1**). This is a key limitation of such studies. It also means that the data required to inform on the success of SDGs have to consider the nature and feedbacks of different variables that operate within environmental and Earth systems. Examining these evidence-based relationships from specific case studies is an important future research priority.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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REVIEW
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Climate Change, Flood Disaster Risk and Food Security Nexus in Northern Ghana

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This research reviews climate change, flood disasters impacts and food security nexus in northern Ghana. The impacts of climate change include flood disasters which in turn affect food production with subsequent impact on food security. While climate change impact can be positive in some regions, it can be negative in other regions as it could lead to excess or lack of water, which negatively affects food production. Most especially, flood disasters have reportedly become frequent with devastating consequences on food production. Literature further suggests that the frequency of floods and their impacts have the potential to increase in the future. Floods inundate farms, pastures and livestock, which could subsequently reduce crop yields and animal production. Floods also destroys physical infrastructure and disrupts socio-economic activities which are linked to agriculture sector and could affect food production. This eventually decreases food availability, accessibility, utilization, and stability in the region. Northern Ghana has experienced flood disasters with increased frequency, which are related to climate change impacts. Although there is research on climate change, flood disasters, and food security issues in northern Ghana, the literature thus far indicates no clear focus of studies that focuses on the nexus of climate change, flood disasters, and food security of the study site. Thus, this research seeks to review the nexus of climate change, and flood disaster impacts on food security in northern Ghana with their implications on food security in the region. This study has two main research objectives. The first objective of this research is to identify and understand the potential impacts of climate change and flood disasters on food production in the study site. The second research objective is to explain the connection between climate change and flood disasters and the implications of this relationship on food security in the study site. This review study focuses on climate change, flood disasters, and food production to understand the critical impacts of climate change and flood disasters on food security in the northern part of Ghana. The aim of this research is to contribute to literature and discussion of the nexus of climate change, flood disaster impacts and food security sub-Saharan Africa.

Keywords: food security, climate change, flood impacts, northern Ghana, nexus

INTRODUCTION

This research analyses climate change, flood disaster impacts and food security nexus in northern Ghana. Climate change and its related impacts on agriculture in societies have attracted development and policy concerns among local, regional, and international levels [Clover, 2003; IPCC, 2007; Food Agricultural Organisation (FAO), 2015]. Literature on climate change suggests that current increase in greenhouse gases from activities of humans and natural events have contributed to high rise in the average global temperatures beyond levels of the pre-industrial era (IPCC, 2014, 2007). Increase in the average global temperatures gives rise to global warming which affects precipitation, sea level rise, tsunamis et cetera. The impacts of climate change on precipitation and increase in sea level rise have resulted in lack and excess of water in regions that could experience floods and droughts (White, 2010). These events have disproportionate impacts on regions, seasons, and sectors of societies. For instance, agricultural sector contributes to the livelihoods and food security of societies but impacts of the climate change related events threaten the sector. In developing nations, especially, the agricultural sector employs a majority of the working population, yet it faces the perils of climate change. The impacts of climate change and its related events on food production and food security are a sharp threat to African countries that already have protracted history of poverty and food insecurity for decades (IPCC, 2014).

The problem in parts of Africa continent has been described as a food crisis due to the high number of people without secured adequate availability, access, utilization, and stability of food year-round [Clover, 2003; Akudugu et al., 2012; Food Agricultural Organisation (FAO), 2015]. In explaining the food security threat in sub-Africa, Clover (2003) reveals how the problem of food security is a pan-African issue that cuts across regions and needs to be understood and addressed. Ngcamu and Chari (2020) studied the impacts of droughts on agriculture in rural Sub-Saharan Africa and confirmed that drought is a threat to food security which requires multi-strategy and multi-stakeholder framework mitigation approaches to ensure resilience to food security. Deressa et al. (2010) investigated climate change and agriculture as a problem with emphasis on the perception and adaptation of farmers to the impacts of climate change along the Nile basin in Ethiopia. Ola (2018) focused on the challenges of climate change of rural dwellers of Esanland in Nigeria and concludes that farmers are vulnerable to the adverse impacts of climate change. With more specific emphasis on floods, Akukwe et al. (2020) studied flooding as climate change hazard and its impacts on food security in southeast Nigeria. Results of their research confirmed that floods negatively affect food security by increasing the number of food insecure households in the study area.

There are several studies about climate change impacts on rural communities and food security in northern Ghana. Chemura et al. (2020) studied the impacts of climate change on agro-climatic suitability of main crops in rural communities with emphasis on savannah crops and confirmed that weather and climate change have impacts on agriculture with sorghum and groundnuts most affected. Musah et al. (2013) in their studies on the effects of floods on livelihoods and food security in Tolon-Kubungu District in the Northern Region of Ghana confirmed that flood disasters affect socioeconomic activities communities that reduce food security in the region. In his studies, Quaye (2008) reviewed the food security situation in northern Ghana with emphasis on the coping strategies and the constraints being faced in the region. The studies indicate that erratic rainfall, droughts, floods, and poor infrastructure seem to dwindle farmers' capacity toward food security in the region. Cooper et al. (2019) studied hunger, nutrition, and precipitation issues in Ghana and Bangladesh, and revealed that the two countries face irregularities in rainfall and the ability to produce enough food for their populations. Agyei (2016) further observed that remittances from migrants contribute to access to farmland and food production toward food security in Ghana. This observation demonstrates that although outmigration may relocate labor away from agriculture in some regions, emigrants, in turn, support to achieve security in their home communities through remittances.

In a different view, Sidibé et al. (2016) contended that there are opportunities for flood recession agriculture along floodplains in Ghana. The basis of this argument is that alluvial soils along floodplains after flooding provide fertile soils for farming activities to contribute to food security. Irrigation projects along floodplains can make use of the fertile soil for agricultural production. The literature further reveals that climate change and variability impact is a threat to crop production in the rain-fed agricultural system in Ghana with the potential to worsen the food insecurity situation of the vulnerable population (Asante and Amuakwa-Mensah, 2014). Relying on natural rainfall for agriculture is unsecured and needs to consider other means for food production. Again, destructions from floods disasters can damage physical infrastructure linked to agriculture and food supply chain which can deteriorate food availability, access, and stability in countries. For instance, Begum (2018) examined climate change related hazards such as droughts, floods, cyclones, and among others as common hazards that affect build infrastructure of countries with spiral impacts on agriculture and food security.

For instance, the ecological zone of northern Ghana carries a higher share of the country's burden of climatic hazards as compared to the southern zone. This is because the ecological zone of northern Ghana, which is already stressed with a high incidence of poverty and food insecurity, is highly susceptible to impacts of climate change (Armah et al., 2010). Over the years, frequencies and incidences of floods have been increasing in northern Ghana. Statistically, major floods occurred in 2007, 2010, 2012, 2017, 2018, and 2019 in the region due to heavy rains and spillage of the Bagre dam in Burkina Faso (Yiran and Stringer, 2016; Fiasorgbor et al., 2018). These flood events posed significant threats to agricultural production and rural livelihoods. Studies have revealed that floods sweep away crops, livestock, and homes which further leads to injuries and casualities (Yiran and Stringer, 2016; Fiasorgbor et al., 2018). The adverse impacts of flood events on the agriculture sector have resulted into perpetual poverty and food insecurity in the northern zone of Ghana (Yiran and Stringer, 2016). For example, The World Food Programme in 2009 reported that ∼453,000 people in Ghana are food insecure with 34% in the Upper West region, 15% in the Upper East, and 10% in the Northern region.

So far, the literatures show that the spate of climate change impacts in societies is becoming obvious and it detracts the global efforts to achieve food security, which is a key sustainable development goal. Studies carried out on climate change in the study area have rather focused on the impacts of specific climate related events such as floods and drought in relation to food security. Thus far, no studies have addressed the nexus of climate change, flood disaster impacts, and food security in northern Ghana. Accordingly, this is a knowledge gap that this research seeks to discuss.

Besides, the section on introduction to the background of this research, the rest of the research is structured into the following sections. The section climate change, flood disasters and food security nexus provided insights into existing research on climate change, flood disasters and food security of the study site. The section on research design and methods describes the study context and methods. The results sections consisted of flood disaster impacts on food production, climate change and flood disaster impact on food production in the study area. Results of the research are discussed in sections on climate change, flood disasters and food security nexus. The that followed next focused on future implications of flood disasters for food security in the study site. The final section focused presented conclusions and recommendations of this study.

CLIMATE CHANGE, FLOOD DISASTERS AND FOOD SECURITY NEXUS CONCEPTS

Climate change is an issue of concern at the local, national and international levels due to its consequences on societies. Literature indicates although the causes of climate change are both natural and human-induced, they are more of the latter than the former (IPCC, 2014). Greenhouse gases such as carbon dioxide and methane can come from natural causes such as decomposition, earthquakes, and natural wetlands but most greenhouse gases are accrued to human activities as the main cause of climate change (IPCC, 2014). Increase in the amount of greenhouse gases in the atmosphere is the main cause of climate change. This increase in greenhouse gases in the atmosphere increases the average global temperatures. The amount of carbon dioxide in the atmosphere became more in the post-industrial age than before, which confirms the significant contribution of humans to the causes of climate change (Maslin, 2008). The mean global temperatures are estimated to stand between 1.4 and 5.8°C in the twenty-first Century with 0.6°C as the average rate of increase (IPCC, 2014). The impact of global warming seems to match with the corresponding increase in the rate of melting glaciers and the rise in sea levels. These predictions of global warming and its impacts may be higher in the future than currently estimated due to uncertainties (Singh and Singh, 2012).

The impact of climate change is not the same everywhere in the world (Clover, 2003). It is obvious that industrialized countries contribute more to global change than developing countries but impacts of climate felt *vice versa*. Whereas average temperatures are highest in the tropics, the temperate, and polar regions have lower temperatures. Consequently, the negative impacts of climate change are worse in economically vulnerable countries than the strong economies (Akukwe et al., 2020). The impacts of floods, droughts, cyclones, tsunamis, and storms due to climate change, are more predominant in tropics than in temperate regions. Global warming with its consequences of prolonged droughts, rainfall variability, and flood disasters has become more frequent in the parts of Africa than before. The spread of pests, diseases, and loss of fauna and flora are also argued to be linked to climate change impacts in societies. Flood disasters have increased, leading to direct, and indirect impacts on societies including agriculture productivity as well as food availability, accessibility, utility, and stability in communities. Akukwe et al. (2020) studied flood-induced food insecurity in parts of Nigeria and argued the impacts could be before and after flood events. Flood disasters physically cause damage to farms, crops, livestock, and physical infrastructure of agriculture and food supply chain to reduce agricultural productivity yields and food availability (Armah et al., 2010). Direct impacts of floods on crops and livestock can cause losses and a reduction in farm yields. Flood disasters can break down transportation networks and access to farms, food markets, and consumption points. Floods can cause financial loss to producers, suppliers, and consumers of food productions which could reduce individual's capacity to afford food in communities (Pacetti et al., 2017). Inability to afford food can reduce the ability to access and utilize food items with the required nutritional values for individuals. Direct and indirect impacts of floods also damage the ability to store food products to make food available to individuals in communities. Food stability hinges on the ability to maintain availability, access, and utility of food items in localities. Food security, therefore, exists where food is available, accessible, affordable, and stable for individuals in communities.

The concept of food security in the 1970s was about having enough food available at the global and national levels without much consideration for whether its accessibility and restriction of supply at local and individual levels. It became clear that available food at the global level does not mean everyone's entitlements to basic food are secured. The local availability and personal level accessibility become paramount. However, one can have access to food but may not be able to afford and make use of the available food with the required nutrition. It is therefore important to consider the ability to utilize and stabilize food for persons in communities for the concept of food security. Food supply should be stable so it can be always available in all seasons. Thus, food security considers factors for comprehensive analysis (FAO, 1996a; Clover, 2003). In the Rome Declaration on World Food Security in 1996, food security is seen as a situation in which food is always available, to which all persons have means of access, that is nutritionally adequate in terms of quantity, quality, and variety, and is acceptable within the given culture (FAO, 1996b).

RESEARCH DESIGN AND METHODS

The Study Area

The focus of this study is on northern Ghana. Ghana is in West Africa and shares borders with Burkina Faso, Togo, Cote d'Ivoire, and the Gulf of Guinea in the north, east, west, and south, respectively. Ghana lies between latitudes 4.50°N and 11.50°N and longitude 3.50°W and 1.30°E. The political demarcation of northern Ghana is linked to the colonial era of the country, the then Gold Coast. During colonial time, this part of the colony was named the Northern Territories with Tamale as the administrative capital. It became northern and upper regions with Tamale and Bolgatanga as regional capital towns, respectively. The upper regions in the 1980s split into Upper East and Upper West regions with Bolgatanga and Wa as regional capital towns accordingly. Since 2018, new administrative regions have been carved out to include the Savannah Region with Damango as a regional capital, and the North East Region with Nalerigu as the capital town. This administrative background captures the current political delineation of northern Ghana.

The geographical description of the study site briefly mentions the biophysical attributes of the study area which influence the socioeconomic activities of the inhabitants. This description offers readers an understanding of the physical environment, the interaction between humans and the environment, and environmental issues of the study site. Northern Ghana can generally be described as high plains with tropical savannah ecological conditions. Northern Ghana has unimodal rainfall season yearly from March to November with further reduction of the season northwards. The rainfall season keeps dwindling and becoming more and more erratic in recent years, seemingly suggests evidence of climate change or variability. The average annual rainfall in the region stands between 700 and 1050 mm. The harmattan seasonal winds blowing from the Saharan desert southwards have dry and hot conditions of between 15 and 40°C annually. The hottest period is December to March. The study site is characterized by tropical savannah flora and fauna. The vegetation is mainly grassland and drought resistant trees, normally useful for the rearing of livestock and growing of cereals. These socioecological conditions indicate challenges and opportunities for agriculture and livelihood activities in the region.

Population density in northern Ghana is generally sparse in rural settings with economically poorer conditions than the southern part of the country (Yaro and Hesselberg, 2010). With high poverty and unemployment rates, the active population in the region emigrates to southern Ghana for livelihood opportunities in dry seasons annually. Thus, the region also serves as a seasonal source of labor for the southern part of the country. Although agriculture is the mainstay of Ghana, higher number of people in the study area rely mainly on rain-fed and irrigation agriculture. Infrastructurally, northern Ghana lags its southern counterpart in national development.

Methods

This research employed thematic data analysis strategy to analyse data from secondary documents. The thematic method of analysis is popular for its ability to illuminate detailed interpretation of qualitative data obtained from secondary sources. Braun and Clarke (2013) explain that this approach is beneficial for obtaining insights from secondary sources of data. Thematic method of data analysis helps researchers to make meaning of textual materials. The strategy is useful further because it has advantage of drawing comprehensive meanings and nuances of the data obtained (Babbie, 2012). Using this method, a descriptive theme is explicit in its expression of the topic being studied and subsequently allows the analyst to sift out a clear interpretation from the textual data. This approach enables researchers to aptly apply the thematic data analysis method to identify and analyse patterns of secondary data sources to explain a scientific problem (Braun and Clarke, 2006). In fact, this strategy allows researchers to reflexively engage with textual data to develop a story from the data (Neuendorf, 2019).

This review research is a synthesis of recent relevant literature covering topics on climate change, flood disasters, and food security nexus in sub-Saharan Africa with specific emphasis on northern Ghana.

Data Search Strategy

The approach to searching for relevant data purposively sought literature from electronic data bases and libraries using general to specific themes of the research. Literature on the broad themes about climate change, flood disasters, and food security was engaged to obtain global perspectives about the problem. This search opened doors to specify the data search to the geographical location and objective relevance of the topic. Thus, climate change impacts and food security nexus, flood disasters and their impacts on agriculture and food security in Africa and northern Ghana were deliberately used in finding relevant literature. To ensure quality and authentic relevant literature sources and peer reviewed publications, covering the themes were considered in the search. Data from such sources as journals of African Security Review, Climatic Change, Environment, and Earth Science were used. Policy and technical documents including those from the Food and Agricultural Organization (FAO), Intergovernmental Panel on Climate Change (IPCC), and the Ministry of Agriculture in Ghana have been informative. Analysis of data from the relevant sources employed specific words, phrases, sentences, and excerpts that describe the specific themes of the literature as useful data. For instance, nexus, climate change, flood disasters, food security, and impacts as well as Sub-Saharan Africa, and northern Ghana helped to identify the most relevant excerpts for careful paraphrasing and interpretation. As recent as literature dating from the year 2000 were used to ensure the information is relevant and speaks to the issues being research. **Table 1** summarizes the key points from the key literature that was explored.

TABLE 1 | Summary findings climate change, and flood disaster impacts drawn from literature.

References	Research focus	Study Context	Methodology	Direct and indirect impacts of floods		Summary
				Direct impacts	Indirect impacts	
Okyere et al. (2013)	Analysis of disasters in Accra	Flood disasters in Ghana	Literature review and secondary data.	Deaths of about 1,133 people from 1980 to 2010 Huge economic costs, Halt businesses, physical damage houses, transportation and communication and other infrastructure.	Eviction of Old Fadama community Outbreak of cholera Long term economic impacts, trauma on individuals.	Floods are caused by natural and human-induced factors and their impacts are devastating to lives and property.
Douglas (2017)	Review of flood disasters in sub-Saharan.	Sub-Saharan Africa	Case studies and secondary data.	Loss of lives and property, diseases, displacement of people and homelessness, damage to road surfaces and inundation of farms.	Increase in food prices, reduction in economic activities, increase in poverty.	Floods are climate change related and caused deaths, economic loss, damage to infrastructure and environment.
Akukwe et al. (2020)	Research question: "Do floods affect food security?	Comparative study of pre- and post-flood households' food security statuses in South-Eastern Nigeria	Quantitative Survey of 400 households in eight communities using stratified and random sampling methods.	Floods affect food security by increasing the number of food insecure households to 92.8% with regression coefficient of −0.798, indicating a very strong negative effect of flooding on household food security.	Flood disasters can make communities food insecurity hotspots which would need long-term food assistance.	Flood disasters are indicative of climate change impacts and they induced food insecurity in the affected communities.
Alhassan and Akudugu (2012)	Impacts of climate change on household food security, livelihoods and social safety in Northern Ghana	Rural areas in Northern Ghana	Observations and desk review method were used.	Decline in rainfall reduce crop yields, pasture for livestock and food availability. Floods damages infrastructure for production, transportation, market structures, storage and processing of food. Floods impacts include financial loss to producers, consumers, and suppliers of food. All reduces food access, utilization, and stability of food.	Inadequate water and after flood events cause diseases and pests which reduce farm yields. Harvested crops get rotten on farms due to wet conditions of floods. Drought conditions also causes food production and fire outbreaks.	Droughts and floods are double tragedy for food security and nutrition safety. Development and implementation of climate change adaptation is recommended for the region.
Abdul-Rahaman and Owusu-Sekyere (2017)	How climate variability affected the production maize, millet, rice, and groundnuts in north-eastern Ghana	North-eastern part in the Upper East Region of Ghana	384 in-depth interviews from 6 communities and climate data on rainfall and temperature variability.	Climate change impacts seen in rainfall variability, reduction in period and heavy downpours, and affect crop production in downward trend. Temperature increases and droughts also affect crop yields.	Excessive rainfall affected the prospects of these crops and crops get rotten on farms.	There is negative relationship between climate variability and food crop production in north-eastern Ghana.
Adu-Boahen et al. (2019)	Assessed climatic patterns, and impacts on food crop productivity	Bawku West District in the Upper East Region of Ghana	Quantitative and qualitative approaches using questionnaire, structured interview guide and field observation.	Destruction of farm, farm produce including maize, millet, rice, sorghum and cowpea, livestock, homes, and food storage and processing facilities. Droughts reduce crop yields and livestock production.	After flood impacts on health, finances and loss of valuables can affect security.	Climate change impacts on rainfall variability and droughts affected food production in the study site.
Braimah et al. (2014)	Assessed the causes of flooding and its attendant socio-economic conditions on the livelihoods of people	Sawaba in the Bolgatanga Municipality of Upper East Region, Ghana	Qualitative and quantitative methods.	Destruction of homes, dwelling houses injury of individuals, loss of property and finances.	Disrupted businesses, and daily activities of people.	Flood caused by heavy rains, poor drainage, waste disposal, and compact soil and poor soil percolation.

(Continued)

TABLE 1 | Continued

References	Research focus	Study Context	Methodology	Direct and indirect impacts of floods		Summary
				Direct impacts	Indirect impacts	
Owusu et al. (2016)	Investigated the degree of smallholder farmers' vulnerability to floods	Conducted in the Tolon District of northern Ghana	Mixed methods, involving qualitative and quantitative approaches.	Flood affected farms located low-lying areas and floodplains, loss and injury to livestock, injured people, damage and loss to property, financial loss and infrastructural breakdown.	Degradation of farmlands and reduction in livestock production.	Farms, livestock and communities are vulnerable to climate change and flood impacts. Mitigation to floods and adaptation to climate change impacts are recommended.
Armah et al. (2010)	Explored impact of floods on natural resource dependent communities	Floods from excessive rainfall and the Bagre Dam in the Northern of Ghana	Survey method with 220 randomly selected respondents.	death of 20 people, loss of livestock, destruction to farmlands, houses, bridges, schools and health facilities, damage to water supply, irrigation systems, food storage and processing facilities in the study area.	Spread of diseases and pests. Wet conditions caused affected crops on farms.	Seasonal variations in agricultural output and floods are less sensitive.
Derbile et al. (2016)	Vulnerability of agriculture to climate variability Upper West Region of Ghana and the policy implications for climate change adaptation planning	Upper West Region of Ghana	Quantitative and qualitative methods.	Floods inundate farmlands, fell and washi away of plants and food crops. After flood disaster cause poor yields, stunted growth, rotting of grains and soil erosion.	Wilting and dying of crops, diseases and pest infestation, Poor seed and tuber development and rotting of harvest.	Smallholder agriculture significantly vulnerable to climate variability in north-western Ghana. The article highlighted three layers of vulnerability, which begins with double tragedy of farmer exposure to droughts and heavy precipitation events.
Sidibé et al. (2016)	Flood Recession Agriculture for Food Security in Northern Ghana	Food Security in Northern Ghana:	Literature review and secondary data.	After flood impacts include fertile Soils in floodplains agriculture, water for irrigation and opportunities for after flood agriculture.	Post agriculture and food production in floodplain areas.	Flood recession is not fully taken seriously although it has a potential in the region to contribute to food security.
Hazran et al. (2017)	Impacts of flood on the farming community in Malaysia	Kelantan farming community in Malaysia	Empirical research using quantity.	Impacts on farms, infrastructure, labors and food security.	Emotional and psychological impacts as well as economic losses.	42.9% of respondents suffered economic losses from flood disasters. The flood negatively affected low-income earners
Jonathan et al. (2020)	Economic effect of flood disaster on food security	Southern guinea savanna zone, Nigeria	Quantative techniques using surveys.	Flood destroys farms, food, homes, social and economic activities. Floods have negative impacts economies of households.	Post flood impacts include psychological and economic impacts.	Increase in flood disaster occurrence leads to more food insecurity of farming communities.
Alhassan (2020)	Effect of on-farm and non-farm flood adaptation strategies on farm households' food security	Food security in the Upper East region, Ghana	Multinomial endogenous treatment effect model was used.	Flood shocks have direct impacts farms which reduce farm yields and induce food insecurity in households.	Indirect impacts is post flood impacts and increase in food shortages in households affected by floods.	Social network, extension services and information on flood occurrences are helpful for adaptation decisions to flood shocks.

CLIMATE CHANGE AND FLOOD DISASTER IMPACTS ON FOOD PRODUCTION

Climate is a primary factor for food production through agriculture activity, such that any change in climate affects plant and animal production (Shongwe et al., 2014). Thus, climate change can affect food production through flood directly and indirectly. Intensification of rainfall extremes (Wasko and Sharma, 2015; Wasko et al., 2016) and increasing volume (Trenberth, 2011; Mishra et al., 2012) have been linked to the higher temperatures expected with climate change. This increase in the possibility of extreme rainfall and its intensity creates a higher risk of destructive flood events that cause a threat to food production, particularly in vulnerable regions where the mechanism or infrastructure has not been designed to cope with these increases. With the increasing frequency of floods associated with climate change, agricultural production will decline to result in a decreased state of food production with high malnutrition (Kumsa and Jones, 2010).

Flooding is by far the most destructive type of weather extremes that strikes humans and their livelihoods around the world (Harvey et al., 2014). In recent times, there have been disastrous flooding experienced globally (Thomas, 2017), with a high proportion of people that suffer its negative impacts living in rural areas, especially in less developed countries (LDC). For instance, rural communities in developing countries are largely affected by these flood extremes due to their high dependence on rain-fed agriculture and their limited capacity to respond to climate-induced disasters (IPCC, 2012).

Ghana is one of the vulnerable countries to floods in Sub Sahara Africa (Aggrey, 2015; Amoateng et al., 2018, Almoradie et al., 2020) with devastating effects, especially for the urban poor and farmers in the northern part of the country (Okyere et al., 2013). For example, in 2017, Ghana experienced extreme floods that affected about 1 million people (IFRC, 2017; Adegoke et al., 2019).

The frequency and severity of floods in northern Ghana over the years have increased considerably (Armah et al., 2010), which has a far-reaching effect on food production in the region. Consequently, floods are among the most regular natural disasters that affect livelihoods especially farming in the region (Owusu et al., 2016). The region's agriculture is typically rain-fed and largely on a subsistence basis with about 90% of farm holdings being <2 hectares in size (MoFA, 2012), thus, the incidence of a flood event directly affects their farm output and livestock. Northern Ghana is considered one of the flood-prone areas in Ghana. For instance, over the years, heavy rainfall, and the spillage of water upstream from the Bagre dam in Burkina Faso have resulted in perennial flood situations. For instance, within a space of 10-year period, 2004 to 2014, the region was traumatized by six (6) different flood events in the following years; 2004, 2007, 2008, 2009, 2010, and 2012. Besides, in 2018, floods caused by high-intensity rainfall combined with water releases from the Bagre Dam in Burkina Faso affected 100,000 people and destroyed 196 km^2 of farmland in northern Ghana (Floodlist, 2018).

The flood events direct and indirect impacts on food crops, livestock, infrastructure and people that can induce food insecurity in northern Ghana. The flood events have caused loss of lives and labor useful for agricultural productivity. Direct physical floods can destroy farm produce and livestock to reduce food availability in communities. During and after flood events, floods can cause damage to food produce as well destroy potential for good crop yields.

The key infrastructure include transportation, food stores, and process factors that are also vulnerable to impacts of floods that can reduce access, utility, and stability of food in the region which also impoverished. For example, the August 2007 floods affected about 3,000 hectares of farmlands and damaged major crops including maize, groundnuts, yam, cassava, and rice. The outbreaks of environment and sanitation-related diseases such as malaria, cholera, and diarrhea amongst children were also noted.

According to studies carried out by Derbile et al. (2016), there are two types of food crop farming risks related to flood in northern Ghana. Floods arising from heavy rainfall is noted as flash flood, which is common form of flood in the region. It occurs annually and may occur several times during the rainy season. The second is heavy floods arising from either prolonged heavy rainfall or high volumes of water originating from higher lands in Burkina Faso. These types of floods do not occur frequently. On average, heavy floods have occurred every 5–10 years over the past five decades. Both forms of floods negatively affect food crop farming in different ways in the region. Flash floods affect food crop production more frequently but the adverse effect is often far smaller than the effects of heavy floods arising from a long period of heavy rainfall. Derbile et al. (2016) identified eight adverse effects of floods on food crop farming in the northern sector of Ghana which includes poor seed development, pest, and diseases infestation, death of crops, soil nutrients erosion, rotting of crops, stunted crops growth, poor yields as well as felling and washing away of plants.

The common impacts are destruction and washing away of plants. Again, Derbile et al. (2016) flood disaster impacts food crop in the region can be inundation in water through which cereals, tubers, and legumes including maize, millet, guinea corn, cowpeas, beans, groundnuts, bambara beans, rice, potatoes, yams, and cassava can die or get rotten on farms besides been carried away from farms. Crops get rotten on farms under wet conditions and poor sunshine due heavy rainfall as well as moisture and moldy weather conditions. Besides, spillage of water from the upstream Bagre Dam causes floods that affect humans, crops, and livestock in the region. These effects lower agricultural productivity and food availability in rural communities and markets. Subsequently, the food security is threatened. The impacts of flood events on road infrastructure, which is the main means of carrying foodstuff to marketplaces as well as storage facilities is also affected. With physical destruction of transportation network and food storage and processing facilities, which are already inadequate, access, and stability of food in the region become major question marks with risk to food security.

CLIMATE CHANGE, FLOOD DISASTERS AND FOOD SECURITY NEXUS

The connections between floods and food security are very relevant, particularly in developing countries where food availability can be highly threatened by flood events which impair food availability, access, utility, and stability at the community, national, and global level through direct and indirect impacts on agriculture (Pacetti et al., 2017). Evidence in the literature exists on the pathways by which floods can affect food security (Funk et al., 2008; Cooper et al., 2019), with subsistence farmers being predominantly vulnerable (Morton, 2007; Awojobi and Tetteh, 2017). The most direct influence of flood due to high rainfall levels on food security is physical flood impact and damage to farms, crop yields, livestock, and decreasing the overall food availability in a location (Hanjra and Qureshi, 2010; Schlenker and Lobell, 2010; Afifi et al., 2014; Cooper et al., 2019). For example, in rain-dependent agricultural economies, erratic rainfall causing unexpected floods can create devastating impacts on the food security of the people and their livelihoods (Ramakrishna et al., 2014, Toubes et al., 2017). The Intergovernmental Panel on Climate Change (IPCC) states in the Fifth Assessment Report with high confidence that climate change will increase the risk of food insecurity through impacts such as flooding and shifting precipitation patterns (IPCC, 2014). While rates of undernutrition and food insecurity have been falling overall for the past few decades, there have been recent increases in these statistics in some locations, which is somewhat attributable to flood shocks (Cooper et al., 2019).

Food security exists when all people, at all times, have physical, social, and economic access to sufficient, safe and nutritious food which meets their dietary needs and food preferences for an active and healthy life (FAO, 1996a,b) According to literature, the four pillars of food security are availability, access, utilization, and stability. Hence, flood risk is connected to all four dimensions of food security. Food availability looks at the "quantities of food available on a consistent basis" and the expression "food access" refers to the possibility to have access to enough food for a healthy diet (Pacetti et al., 2017). Food utility is defined as the ability to use it for nutrition and care, which is linked to adequate water and sanitation. A decrease in food availability can have constraints on food access: when yields and livestock productivity decrease, food prices increase, making food access difficult for poor households (Devereux, 2007; Webb, 2010; Brown and Kshirsagar, 2015). At the same time, households that rely on sales of agricultural products can experience decreasing incomes, while those relying on agricultural wage labor or trading with farmers can also be negatively affected (Pandey et al., 2007; Cunguara et al., 2011; Bola et al., 2014; Udmale et al., 2015). Finally, excessive rainfall can increase the risk of infectious diseases such as malarial, parasitic, and diarrheal disease, in turn harming proper food utilization and increasing rates of undernutrition (Delpla et al., 2009; Paterson and Lima, 2010). Pacetti et al. (2017) also concluded that flood events will lead to a reduction in farm produce and livestock, destruction of stored food, damage of cultivation site due to soil erosion, and destruction of feeder roads to farmlands. All these parameters of food security and therefore reflects the link between flood and food security.

Floods and their impacts on food security in northern Ghana is not a new phenomenon, and whenever heavy floods hit, farm crops and livestock would be one of the severely affected properties owing to their vulnerability with respect to flood events. Evidence of relationships between flood events and food security is clear in northern Ghana, relative to other parts of the country. For instance, due to the periodic excessive rainfall coupled with the spillage of excess water upstream from the Bagre Reservoir in Burkina Faso, extensive floods in many districts of the region have occurred. Consequently, these floods have caused severe damage including the loss of livestock, the destruction of farmlands, as well as damage to water supply, irrigation systems, food storage, and processing facilities. Besides, many of the flooded areas are often inaccessible due to the breakdown of key infrastructure, including bridges and roads. According to assessments carried out by the Ministry of Food and Agriculture (MoFA), about 70,500 hectares was affected (Armah et al., 2010) resulting in an estimated production loss of 144,000 Metric Tons (MTs) of food crops (including maize, sorghum, millet, groundnuts, yam, cassava, and rice). As a result of flooded roads and submerged bridges, not all food commodities were readily available at all markets. An estimated 50,000 people in Northern Ghana were expected to remain vulnerable to food insecurity and at risk of malnutrition for at least 15 months beyond the early harvest in October 2008 (UNOCHA, 2007; Armah et al., 2010). Also, the main diet in most Ghanaian homes constitutes mostly cereals—millet, sorghum, maize, and rice—which are produced mainly in the Northern part of Ghana. A decrease in the production of these commodities because of flood events would deteriorate the already alarming threat of food security, particularly in the northern sector of Ghana, and severely affect the economic development of the region (Adu-Boahen et al., 2019). Again, Armah et al. (2010) posited that in some parts of Northern Ghana, flooding during August and early September 2007, led to the destruction of key infrastructure, food stocks and livestock, which contribute to food insecurity in the region.

IMPLICATIONS OF FLOOD DISASTERS ON FOOD SECURITY IN THE STUDY SITE

Climate change related events including prolonged droughts and floods affect food security in the site (Baba et al., 2018). Akudugu and Alhassan (2013) demonstrated that climate change in northern Ghana affects food availability, access, utility, and stability spiral impacts on household nutrition of individuals. Northern Ghana is largely rural livestock keepers and agricultural producers using rainfall and irrigation. The climate change impacts and rainfall variability, the main concern of flooding has been the destruction of farms, food crops, livestock as well as seeds stores, resulting in a decline in food production. A decline in food production can lead to starvation which may in some cases last several months after each episode of floods (Akukwe et al., 2020). Starvation together with a decline in environmental quality resulting from flood related damage promotes the desire of people to migrate out of these rural areas. The reduction in food production resulting from floods also means loss of income for people in these communities which further reduces their ability to purchase food and thereby contributing to increase the problem of food shortages and starvation within households. Also, one important aspect of floods in northern Ghana is the damage they inflict on seeds. Most small-scale farmers safeguard the most viable portions of their produce as seed for the next planting season (Akudugu and Alhassan, 2013).

In the 2007 floods, significant damage of food crops just nearing harvest meant that the farmers' seed supply for the coming agricultural year was jeopardized. Floods may therefore affect seed supply either through affecting crop production (on farms) or destroying seed stores (in homes). Either way, the lack of seeds for subsequent planting could generate a reinforcing effect of lower food production and another resulting lack of seeds. Farmers may be able to supplement their seeds with limited bought supplies—either to make up for a deficiency or introduce produce with better traits into their stock. However, by reducing food production, floods may limit household income and reduce farmers' ability to buy seeds which also creates another reinforcing effect of lower production and even lower ability to increase household income enough to afford seed purchases (Owusu et al., 2016). Though many households in northern Ghana depends on poultry and livestock rearing for livelihoods, diseases, and pest caused by the frequent flood events undermine production (Armah et al., 2010). Also being the poorest and most agricultural dependent region of Ghana, the impact of flood is devastating. A clear example is the 2007/2008 prolonged drought season which was followed immediately by a devastating flood in entire Northern Ghana. Several food crops and livestock were destroyed (some washed away by the flood) causing severe food shortage; farm income declined; buildings, roads, and other infrastructure collapsed; yield from crops declined and countless people were rendered homeless (Nti, 2012).

The direct and indirect impacts of floods on farms, food produce, livestock, physical infrastructure, and labor dwindle the amount of food that can be available to farmers and markets for consumers. Destruction of farmlands and agricultural infrastructure reduces how much food can be available. Access to food relies on transportation network which is also damaged by flood impacts to reduce the capacity to convey food to communities in need. During and after flood events, emergency food aid gets to communities outside through transportation. Where there is a breakdown of infrastructure, this can be a problem. Utility of food when available also based on ability of communities to transform the food stuff into consumable state with required nutrients. This will require converting the food from raw state to cooked state. Food production in the region is highly seasonal and requires storage system or regular marketplace to ensure stability of supply to people in communities. Impacts of rainfall on storage systems can be destructive to food security.

CONCLUSION

This study was set out to review climate change, flood disasters impacts and food security nexus in northern Ghana. Evidence of the review identified the impacts of climate change in region as extreme weather-related events as droughts, rainfall variability, and flood events. Evidence from the literature suggested that floods events from extreme rainfall and spill of Bagre Dam are climate change related events have the potential disrupt agricultural production and food security in northern Ghana. The results further demonstrate the connection between climate change and flood disasters with implications for worsening food insecurity in the study site. Climate change impacts are seen in droughts, rainfall variability and frequent flood events in the region. Flood disasters affect food availability, access, utility and stability in the region as food insecurity seems to be a common problem. Climate change and flood events seem to be on the increase and could potentially deteriorate the undesired food security problems in the region if not addressed.

A major limitation of this research was seen in the limited focus on flood disaster events and the inability to engage with primary data for the analysis of issues. This shortfall did not allow the researchers to have practical primary evidence to make emphatic assessment of the connection between climate change, flood disasters, and food security in the study site.

Climate change related events in region are obvious with clear reduction in the rainfall season, erratic rains, prolong droughts, and flood disasters. These climates related events affect food production with subsequent impact on its availability, access, utility, and stability in the communities and households. Reportedly, floods have become frequent with devastating consequences on food production. Literature seems to suggest that the frequency of floods and their impacts could potentially increase in the future. Floods inundate farms, pastures, livestock, food storage and procession facilities, and infrastructure which could reduce crop yields and animal production. Generally, these impacts could affect future food security in the region if not curbed.

To reduce the impacts on food security in the region, climate change and flood disaster impacts mitigation need to be practiced. One potential advantage of after flood events is flood recession agriculture in flood plains in the region. Traditional crops of the region can be modified to adapt to climate change conditions by crops with short maturity periods. Animals and food storage systems need to be sited on highland areas that have low flood risk. Flood waters should be harvested in dams for irrigation agriculture. Alternative means of food supply and livelihood strategies need to complement over reliance on agriculture in the region.

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All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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Food Security and Coping Strategies of Rural Household Livelihoods to Climate Change in the Eastern Cape of South Africa

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Although governments across the globe have pledged resources and efforts to minimise the factors contributing to climate change, it is a concern that climate change continues to exert significant hardship on many rural communities of which South Africa is no exception. The Eastern Cape Province in South Africa is one of the driest provinces with prolonged water scarcity challenges. The purpose of this study is to investigate coping strategies adopted by the rural poor to build resilience against food insecurity. Primary data was collected from a total of 385 respondents in three rural communities using semi-structured questionnaires and interview. The findings suggest that farmers have been proactive in responding to climate change and food security. The study revealed that farmers are engaged in different coping strategies to ensure that there is enough food for the household. Although some of the coping strategies might assist, others would have severe consequences on the health of the population, especially children. Based on the findings, it is recommended that there should be regular engagement by the local municipality, the community and rural farmers on climate change events. The focus should be on the management of drought, heatwaves, flood, and soil erosion. The government within the local municipality should also focus on building a dam for rural farmers. The dam will serve as a reservoir of water for irrigation during drought.

Keywords: food security, coping strategies, climate change, rural communities, South Africa

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INTRODUCTION

Climate change (CC) has now become recognised as a global challenge. Romm (2018, p. 2), for example, concludes that "the warming of the climate system is an unequivocal and consolidated fact". There can be no contestation or denial of this fact. Climate change adversely affects families, communities and the economy in general and is also argued to be one of the major drivers of environmental change facing many countries, particularly those in the developing south, Samset et al. (2018), for example, have established that regions with high population growth experience greater variations in temperature, precipitation and extreme weather conditions and these combine to trigger environmental changes. In addition to environmental changes, Cunsolo and Ellis (2018) believe that changes in climate variability impact people's mental health and well-being and this can adversely affect their ability to engage in productive activities.

Considering this observation, Kulkarmi and Leary (2007) support an urgent institutional and political response to reduce the impacts of climate change on both the biological and socio-economic sectors of a country's economy.

South Africa, as a country, has had its share of climate change induced challenges, among which include increased flood and drought episodes. These extreme related weather events have had a negative impact both on urban and rural productivity but the worst affected have been rural dwellers (Ngwenya and Simatele, 2020). Furthermore, Unganai (2009) observes that climate induced weather events have resulted in many natural disasters in South Africa and have contributed to increased food and water insecurities in many parts of the country, especially the Eastern Cape. He observes that the heavy dependence on climate-sensitive economic sectors, such as agricultural productivity and mining, makes South Africa vulnerable to any changes in climate (Unganai, 2009). In the context of the high poverty levels (56%) which the country suffers from, the impacts of climate change will have severe consequences on the rural poor people who are highly dependent on agricultural productivity for their livelihoods and income generation and have no or minimal assets portfolios to deploy and build their resilience and adaptive capacity (see Department of Environmental Affairs, 2013; Port Saint John's Municipality, 2018; Singh, 2019).

This paper, therefore, discusses the impacts of climate change on the livelihoods of the rural households in the Eastern Cape and the adaptation strategies which they employ to reduce or minimise the impacts of climate change induced extreme events. It is worth noting that many of the rural households in the Eastern Cape including in the study sites are dependent on rainfed agriculture to produce the food crops such as cereals (maize), vegetables and fruits (Port Saint John's Municipality, 2015, 2018). These crops are climate sensitive and any weather changes affect their yields.

SUSTAINABLE LIVELIHOOD FRAMEWORK (SLF)

This study is rooted in the sustainable livelihood framework (SLF). The SLF focus is on people-oriented ability to utilise their available assets to build capacity and to achieve life goals that are beneficial to their well-being (Karki, 2021; Woyesa and Kumar, 2021). Fundamentally, sustainable rural livelihoods address how the poor in rural areas can cope, secure and overcome the stress of shock (e.g., extreme weather condition) to better their lives (Chambers and Conway, 1992; Karki, 2021). Furthermore, livelihood is deemed sustainable when people can effectively adapt their assets (e.g., natural, physical, social, financial, and human) and emerge as victors to shocks such as changes to seasons without destroying the natural useful resource base (Karki, 2021). Based on the foregoing definitions, it can be argued that rural livelihood is built on a combination of factors such as effective subsistence agricultural methods employed by the household to produce and supply food; access to land; and access to the skills needed to create viable non-agricultural employment opportunities that would ensure the survival of the household over the long-term period (Bebbington, 1999). Rural livelihoods which is the focus of this study can be influenced by the spatial setting, social and economic (e.g., capital) conditions prevailing within PSJ Local Municipality (Eriksen et al., 2005). Most households at the three study sites namely Mgugwana, Manaleni, and Ndayini are expected to perform certain activities and adopt strategies to generate a livelihood. A household uses its livelihood capital to perform activities to generate income, garner social support, and gather resources to sustain itself. These activities include subsistence agriculture (involving but not limited to the growing of basic foodstuffs such as maize, cabbage, carrot), the collection of natural resources, livestock rearing and herding, and informal employment (e.g., hunting, carrying out shoe repairs, sewing and weaving, hawking).

CLIMATE CHANGE AND ADAPTATION STRATEGIES

CC has been explained as extreme weather conditions which extend for a prolonged period, ranging from months to years (World Meteorological Organization (WMO), 2016). Climate change has also been described as an "emerging stressor" that results from extreme weather conditions (Connolly-Boutin and Smit, 2016). It is mostly driven by natural or human influences or both (Cubasch et al., 2013). Human influence is characterised by factors such as population growth, economic activity, lifestyle, energy use, land use patterns, technology, and climate policy (Intergovernmental Panel on Climate Change (IPCC), 2014). Like many other parts of the world, research on climate change in South Africa is an environmental problem, rather than a developmental one. Despite the anticipated negative impacts of CC on the environment to both present and future circumstances concerning food security, existing literature proposes that numerous countries in Africa are not beneficiaries nor contributors of food assistance to the global effort on food security.

In South Africa, climate change does not only manifest itself in higher temperatures but also, in floods and persistent droughts (Turpie and Visser, 2013). It has been predicted that by 2050 and beyond under high emission scenarios, South Africa's weather conditions will show very significant warming, as high as 5–8 °C, over the interior (Long-Term Adaptation Scenarios flagship research programme (LTAS), 2013). A general pattern of risk of drier conditions to the west and south of the country and the risk of wetter conditions over the east of the country is also projected. Many of the projected changes of climatic conditions are high, raising many uncertainties such as extreme warmer or too much rainfall (e.g., flooding) (Long-Term Adaptation Scenarios flagship research programme (LTAS), 2013). These negative weather events, together with the country's already stressed water resources, are expected to affect the rural livelihood and the economy at large (Turpie and Visser, 2013). Although climate change and its effects impact both the wealthy and the poor, available scientific evidence suggests that the rural poor are the most hit (Kabir and Serrao-Neumann, 2020). The prevailing projections of climate change events require an assessment of how the rural poor are exposed to climate change and their adaptive strategies.

Adaptation strategies are changes and strategies implemented to reduce the impact of climate change (Ford et al., 2015). Adaptive strategies include initiatives such as changes made to build environments, the delivery of government services, organisational mandates, or regulations in response to the impacts of climate change (Ford et al., 2015). Stock et al. (2019) argue that knowledge enhancement on adaptation strategies for farmers should be decentralised to community-level institutions. This practise will enhance their efficiency to address climate change risks more proactively. Knowledge by the community on adaptation strategies is of utmost importance to prepare for both long-term and short-term climate change risks (Clarke et al., 2019). Innovative farming practises is also important to minimise community vulnerability and escalate resilience in the long-term (Clarke et al., 2019).

Pinto et al. (2012) conducted a study in Ghana and offered four options on adaptation strategies. The first strategy relates to dealing with risk and uncertainty (e.g., this include indigenous knowledge, weather, and climate information services and early warning, crop insurance, raising of awareness and access to information). The second option relates to farming practises and technology (e.g., drought-resistant varieties, soil conservation and erosion control, crop diversification, and specialisation, irrigation). The third option involves off-farm practises and strategies (e.g., improve post-harvest, food storage practises, migration, empower communities, and females). The fourth option emphasises on national development policy on adaptation strategies to CC (e.g., agricultural intensification and land use policy, access to and governance of water, institutional reforms).

Alemayehu and Bewket (2017) also studied smallholder farmers' coping and adaptation strategies to climate change and variability in the central highlands of Ethiopia. Their research involved 200 farm holders in three districts, three focus group discussions and three informant interviews in each district. In their findings, it emerged that various local farming adaptation strategies have been used by farmers. These strategies were grouped into four categories. The first category was land management (social and water conservation, tree planting, irrigation and fertiliser, and manure (dung) application). The second adaptation strategy was crop management (changing planting dates, crop diversification and the use of drought-tolerant and fast-maturing crops and improved seeds). The third adaptation strategy was livelihood diversification and adjustment (off-farm income, seasonal migration, change in consumption pattern, taking credit, land renting, and remittance). The fourth adaptation strategy was livestock management (decreasing the population of livestock, the use of cross-bred livestock and diversification). Their findings also revealed that the selling of livestock was the most widely coping strategy, followed by changing consumption pattern. Changing crop planting dates emerged as the most preferred adaption option. Only a few surveyed farmers (10%) utilised irrigation as an adaptation strategy.

In a different study on adaptation strategies, Epule et al. (2017) assert that because maize yields in the north of Uganda are more vulnerable to droughts, there should be better ways of making maize production more resilient to the severity and continuous drought. Strategies such as agroforestry, irrigation, agro ecology-based organic nutrient inputs, research, training and innovation, and information diffusion was proposed as key adaptation strategies (Epule et al., 2017). Furthermore, Bawakyillenuo et al. (2016) explored the adaptation strategies to climate change and climate variability in selected villages in the rural northern savannah zone of Ghana. The villages were selected from the Savelugu Nanton, West Mamprusi and Kassena Nankana East Districts. It emerged from their findings that adaptation strategies used by the rural farmers include intensification of irrigation, integration of livestock production, changes in tillage practises, fertiliser and other inputs application on farms, shift from agriculture to non-farm jobs, seasonal migration and purchase of drought insurance for maize (Bawakyillenuo et al., 2016).

IMPACTS OF CLIMATE CHANGE ON FOOD SECURITY

Studies have confirmed that climate change undermines food security (Intergovernmental Panel on Climate Change (IPCC), 2014). This is significant in many parts of the world especially in developing countries (Magdoff and Tokar, 2010). In Africa, food insecurity is due to factors such as extensive reliance on rainfall for crop production, high seasonal variability, recurrent droughts, and floods that affect both crops and livestock (Boko et al., 2007). Climate change affects food production in several ways ranging from direct effects on crop production such as changes in rainfall leading to drought or flooding, or warmer or cooler temperatures leading to changes in the length of the growing season, as well as changes in markets, food prices and supply chain infrastructure (Intergovernmental Panel on Climate Change (IPCC), 2014).

MATERIALS AND METHODS

This study was conducted in three rural communities (**Figure 1**) in Eastern Cape, South Africa between 5 May and 18 October 2018 in three rural communities within Port St. John's Local Municipality. In order to select the rural communities for the study, a complete list of all the rural communities was sourced from the municipality's website. These communities had been grouped under various wards. The lottery technique was adopted and this resulted in Mgugwana, Manaleni, and Ndayini locations being selected for the study (see Cartography map of the marked study area in **Figure 1**). Although the lottery technique was used in selecting the study site, these communities have unique common characteristics such as poverty, high unemployment, and the fact that no research could be found that investigated the impact of climate change on these communities and their adaptations thereof in relation to food security. The lottery technique was employed to randomly select the study site and offered an equal opportunity for each location to be part of the study. The latter minimised the effect of being biassed in choosing the study area.

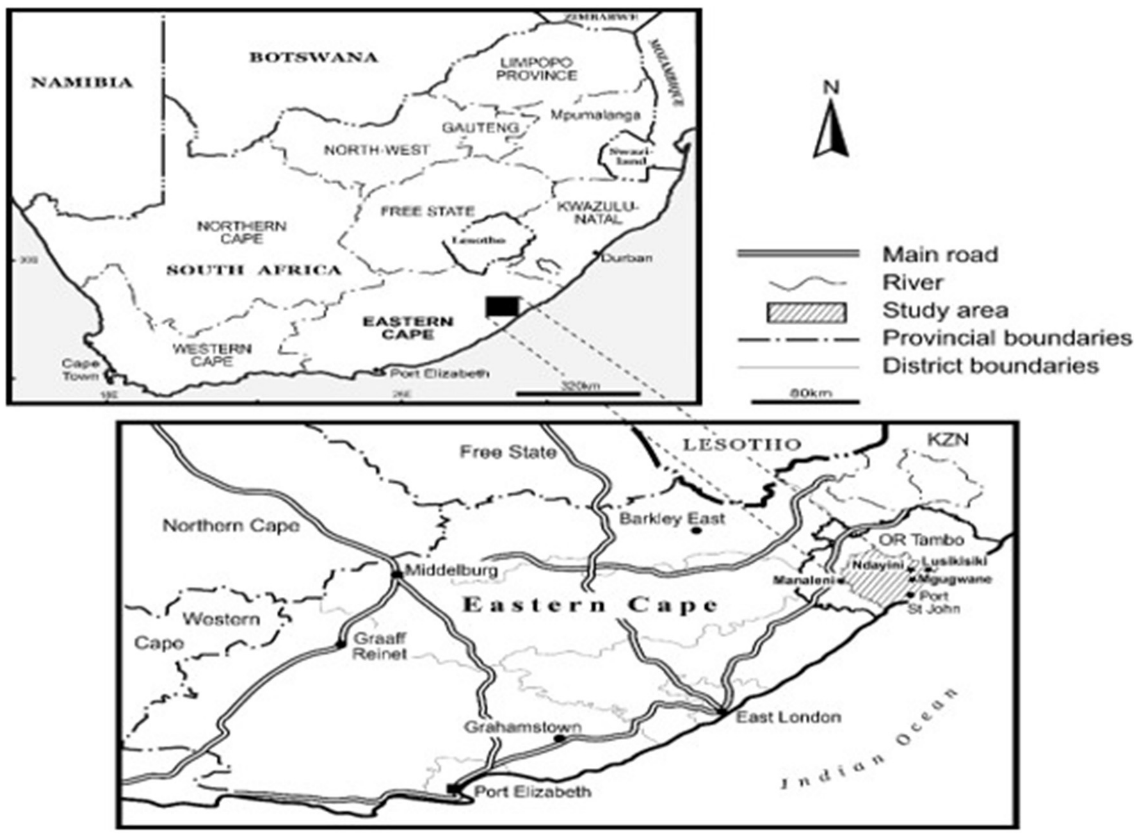

FIGURE 1 | Location of study sites in Eastern Cape Province. *Source:* Cartographic Unit, University of Witwatersrand (2018).

Both quantitative and qualitative research methods were employed in collecting and analysing the data in the study. The decision to combine both qualitative and quantitative research techniques were made to provide a more comprehensive understanding of the research problem (Creswell, 2014) and to compensate for the limitations of the other methods and thus provide a diversity of responses from the participants (Zachariadis and Scott, 2013; Creswell, 2014). The target population for the study involved all subsistence household farmers who reside at Mgugwana, Manaleni, and Ndayini locations. These farmers should have lived in the location for a minimum of 2 years and embarked on some form of farming in the location over this period. The nature of their farms could range from small backyard or compound farms to a large-scale subsistence farm. Both males and females were involved in the study but only those aged over 18–65 years were interviewed. Individual or household farmers were purposefully targeted.

The data were collected using semi-structured questionnaires, focus group interviews, and participant's observations. The semi-structured questionnaires were handed over to individual household farmers from the three study sites to be completed. Where necessary the researcher assisted participants, who could not read nor write to complete the interview questionnaire. Both open-and closed-ended question were used in the questionnaire. Open-ended questions were included to enable participants to express their personal experiences regarding climate change, food security, adaptation strategies, and their impact on the community. Closed-ended questions provided some choice of answers for participants to select. Two focus groups interview was held in each of the three locations. The groups were relatively small and consisted of an average number of between 6 to 12 participants of which 50% were men and the other 50% were women. The groups comprised of both adult female and male participants aged between 19 and 65 years. All the members of each focus group were purposefully selected farmers from the locations. Permission was sought from them if they want to be part of the focus group interview. Two separate discussions were held. In the first round of the discussion, the women had their separate discussion and the men also had their separate discussions. The rationale of the separate discussions was to eliminate the potential possibility where men are assumed to be the head of the household in most rural communities and are only expected to talk during meetings. This would have compromised the intended objective of the group interview. In the second round of discussions, both sexes were brought together in one compound to express their opinions on the issue at hand in the area. Unstructured questions were asked throughout the discussions to allow members of the group to share their opinions, ideas and reactions on climate change and its impact on their available assets. During the group interview, all participants were constantly informed that their inputs are valuable, and they can disagree with each other if it was necessary. The researcher compiled detailed notes that emerged during the discussions. An effort was made to create a tolerant environment in the focus group that would give confidence to participants to share perceptions, points of view, experiences, wishes and concerns without forcing the participants to reach an agreement. Another approach used in the study to observe the respondent's activities was transecting walks. This involved making unplanned visits to the study sites, walking around the farming sites and talking to rural farmers. Maximum effort was made to ensure that the researcher remained neutral during the participatory observations.

Based on the 2011 census data, it was documented that a total of 1,281 (750 + 252 + 279) respectively reside within the selected areas. Considering logistical constraints, it was purposefully decided that a 5% margin of error for a sample size will be suitable for each location. Using the Raosoft sample size calculator, resulting in a total of 296 samples at 95% confidence. However, the sample size was increased to 385 (225 from Mgugwana, 76 from Manaleni, and 84 from Ndayini) to enhance the reliability of the findings. A proportional ratio was used to establish the new sample size per study site. However, the selection of individuals and households were all drawn using the systematic sampling technique. The Raosoft calculator is used to provide a high degree of certainty regarding sample size confidence interval (Raosoft, 2004; Hightower and Scott, 2012; Paz-y-Miño-C and Espinosa, 2016). All the closed-ended questions and answers provided were organised in frequency tables and graphs. The open-ended and focus group aspects of the questions were analysed qualitatively which involved transcribing and identification of themes from the answers provided. Similar answers provided during the focus group interview were grouped and reported as a theme. In most cases, answers provided in the open-ended questions were also reported verbatim.

Reviewers and experts were engaged to help ensure content and face validity of the interview guide and questionnaire. Their suggestions offered valuable contributions to improving the overall measuring instrument. The first reliability procedure followed was to appoint a second person who was not involved in the research process to independently code the data. This allowed the achievement of interobserver reliability (Thyer, 2010). The second reliability procedure followed was to stay close to the empirical data and provide accurate descriptive, verbatim accounts and subjective meanings of the participants. Ethical clearance was obtained from the University of Witwatersrand before commencing with the data collection.

RESULTS

Impact of Climate Change on Food Security

According to Meteoblue (2021), the average precipitation of Port Saint Johns varies and ranges between 18 and 92 mm. The average hot days is 38 °C. Cold nights are between 4 and 16 °C. Singh (2019) asserts that the region experience repeated adverse weather conditions, ranging from severe droughts to extreme precipitation and severe flooding that negatively impacts the lives of the poor.

The researcher asked questions that required the research respondents to state what kind of weather patterns they have experienced over the past 10–15 years. **Table 1** below presents the data obtained which shows that a large proportion of the respondents from the three study sites (Mgugwana 72.0%, Manaleni 64.5%, Ndayini 84.5%) view the summer season as the period where climate change becomes a serious problem to the household.

Furthermore, respondents were asked how they have experienced climate change in their farms. As reflected in **Table 2**, majority of the respondents (91.6% from Mgugwana, 90.8% from Manaleni, and 96.4% from Ndayini) considered drought as a major weather event that has occurred in the area.

Respondents were also asked whether climate change influence food security in the area. It emerged from **Table 3** that

TABLE 1 | Seasons that climate change becomes a severe problem.

	Mgugwana		Manaleni		Ndayini	
	Freq	%	Freq	%	Freq	%
Summer	162	72.0	49	64.5	71	84.5
Winter	59	26.2	26	34.2	10	11.9
Autumn	3	1.3	1	1.3	2	2.4
Spring	1	0.5	0	0	1	1.2
Total	225	100	76	100	84	100

Source: Fieldwork based data (2018).

TABLE 2 | Type of climate change affecting the rural households.

	Mgugwana		Manaleni		Ndayini	
	Freq	%	Freq	%	Freq	%
Floods	19	8.4	7	9.2	3	3.6
Drought and heatwave	206	91.6	69	90.8	81	96.4
Total	225	100	76	100	84	100

Source: Fieldwork based data (2018).

TABLE 3 | Influence of climate change on food security.

	Mgugwana		Manaleni		Ndayini	
	Freq	%	Freq	%	Freq	%
Yes, climate change influence food security	209	92.9	74	97.4	81	96.4
No, climate change does not influence food security	16	7.1	2	2.6	3	3.6
Total	225	100	76	100	84	100

Source: Fieldwork based data (2018).

92.9% of respondents from Mgugwana, 97.4% from Manaleni, and 96.4% from Ndayini were of the view that climate change has an influence on food security in their respective locations. The large representation of the respondents thus suggests that climate change has an impact on food security.

Furthermore, respondents were requested about their experience of climate change since they embarked on farming in the past 15 years. The data received are displayed in **Table 4**.

A closer examination of the data presented in **Table 4** revealed that a large proportion of the respondents from Mgugwana (92.9%), Manaleni (84.2%), and Ndayini (84.5%) experience increase recurrence of drought. It was also found from the three study sites that planting date often changed for most crops cultivated by the respondents. For instance, at Mgugwana (59.1%), Manaleni (51.3%), and Ndayini (57.1%) respondents agreed that their planting date for most of their crops changed due to climate change. An increase in several pests or rodents also emerged as a major problem to farmers during extreme weather conditions. Furthermore, most of the respondents from all the study sites were of the view that there has been a decrease in the recurrence of floods. There were mixed indications on the issue of more heavy rains. Many of the respondents from Mgugwana (61.8%) disagreed that there has been more heavy rainfall over the past 15 years. However, at Manaleni (63.2%) and Ndayini (61.9%) respondents agreed that there has been more heavy rainfall over the past 15 years.

The evidence gathered also shows that majority of the respondents from the three study sites were unanimous that temperature in the locations is increasing instead of a decrease in temperature. Many of the respondents from Mgugwana (83.1%), Manaleni (77.6%), Ndayini (78.6%) were also of the view that they obtain rain later than normal. The above data point to the view that climate change influence food security within the study context.

The impact of climate change on food security was also vividly described by participants in the focus group interview. One of the participants, a female aged 54 years and resides at Ndayini stated:

> *Our biggest problem as peasant farmers in this area over the years has been continuous dryness, heatwaves, and less rainfall. As you can see, we depend on rainfall in our farms. Our farm production depends on rainfall. Most of our crops wither, damaged (dry) due to severe sunshine or high temperature (humidity). We sometimes do not get anything from what we planted, absolutely nothing to harvest from these crops. We do not have irrigation facilities which we can use to get water from the river. Hunger is a common problem here. Because of drought in our community, farming is no longer attractive, especially to the youth.*

To build on this observation, another female farmer aged 46 years and a single parent of two children highlighted:

> *We farm but we do not get anything from farming because of drought. Our food production has reduced drastically due to high temperature. On some days I must beg my neighbours for food before I and my children can eat.*

A male farmer from Mgugwana aged 49 years also indicated that:

> *Last year two of my cattle died because of dryness of the grass and hunger. Our livestock is severely impacted by high temperatures. They do not get greener pastures to feed on, lose weight and sometimes die.*

Another male farmer aged 52 years from Manaleni recalled and shared this:

> *In 2014, there was heavy rainfall continuously for more than 3 days. Our crops were affected because the water settled on the land resulting in most of our crops getting rotten.*

The evidence presented above suggests that climate change impacts food security, especially in the three study sites.

Respondents were also asked to indicate to what extent does climate change affect food production on the local people's livelihood. A large proportion of the respondents (see **Table 5**) (Mgugwana 90.7%, Manaleni 72.4%, Ndayini 89.3%) consider climate change as highly affecting their food production.

Adaptation Strategies to Ensure Food Security

In order to obtain data on adaptation strategies, several questions focusing on adaptation strategies were posed to the respondents. Firstly, the researcher asked whether participants have changed any of their farming practises in order to adjust to climate change. In **Table 6**, the evidence gathered from the three study sites revealed that majority of the respondents from Mgugwana (85.3%), Manaleni (93.4%), and Ndayini (78.6%) have changed their farming practises during extreme weather conditions. The findings expressed suggest that climate change influence farming practises. Lack of knowledge of alternative farming practises will negatively influence food security.

DISCUSSIONS

The field survey data highlights that climate change becomes a serious problem for the rural poor during the summer season. Summer is a period where most South African farmers prepare the land and plant their crops or seeds. It is also a period where farmers expect rainfall to grow their farm produce. Farmers in all three study sites indicated that drought and heatwaves are climatic challenges affecting their farm produce. Given this finding, it can be argued that respondents from the three study sites know that summer is the season that farmers in the rural locations experience severe drought and heatwaves which adversely impact on their farm produce and their livelihoods. It is important therefore to sensitise rural dwellers and farmers within the study area to consistently prepare and build capacity during the summer season to address the impact of drought and heatwaves in the area. A significant number of respondents from the three study sites confirmed that climate change has a significant influence on food security in the community. The findings confirm the assertion made by Turpie and Visser (2013) that unfavourable weather events such as heat waves and drought affect the rural poor. Similarly, the findings are in line with the Intergovernmental Panel on Climate Change (IPCC) (2014)

TABLE 4 | Experience with climate change on farming in the past 15 years.

	Mgugwana		Manaleni		Ndayini	
	Yes	**No**	**Yes**	**No**	**Yes**	**No**
More heavy rains+	86 (38.2%)	139 (61.8)	48 (63.2%)	28 (36.8%)	52 (61.9%)	32 (38.1%)
Getting rain later than normal	187 (83.1%)	38 (16.9%)	59 (77.6%)	17 (22.4%)	66 (78.6%)	18 (21.4%)
Planting date change applying to most crops	133 (59.1%)	92 (40.9%)	39 (51.3%)	37 (48.7%)	48 (57.1%)	36 (42.9%)
Temperature of the area increasing	173 (76.9%)	52 (23.1%)	55 (72.4%)	21 (27.6%)	64 (76.2%)	20 (23.8%)
Temperature of the area decreasing	76 (33.8%)	149 (66.2%)	22 (28.9%)	54 (71.1%)	33 (39.3%)	51 (60.7%)
Decrease in recurrence of floods	123 (54.7%)	102 (45.3%)	61 (80.3%)	15 (19.7%)	59 (70.2%)	25 (29.8%)
Increase in recurrence of droughts	209 (92.9%)	16 (7.1%)	64 (84.2%)	12 (15.8%)	71 (84.5%)	13 (15.5%)
Increase in number of pests or rodents compared to previous years	126 (56.0%)	99 (44.0%)	43 (56.6%)	33 (43.4%)	52 (61.9%)	32 (38.1%)
Other	18 (8.0%)	207 (92.0%)	6 (7.9%)	70 (92.1%)	14 (16.7%)	70 (83.3%)

Source: Fieldwork based data (2018).

TABLE 5 | Extent at which climate change affect food production.

	Mgugwana		Manaleni		Ndayini	
	Freq	**%**	**Freq**	**%**	**Freq**	**%**
Least affecting	1	0.4	0	0	0	0
Affecting	20	8.9	21	27.6	9	10.7
Highly affecting	204	90.7	55	72.4	75	89.3
Total	225	100	76	100	84	100

Source: Fieldwork based data (2018).

TABLE 6 | Changed farming practises in order to adjust to climate change.

	Mgugwana		Manaleni		Ndayini	
	Freq	**%**	**Freq**	**%**	**Freq**	**%**
Yes, changed farming practises	192	85.3	71	93.4	66	78.6
No, never changed farming practises	33	14.7	5	6.6	18	21.4
Total	225	100	76	100	84	100

Source: Fieldwork based data (2018).

report which cautions that future climate events will be dominated by heat waves, droughts, floods, cyclones, wildfires and climate-related extreme impacts that can cause significant vulnerability and exposure to some ecosystems.

Drought emerged as a major climate change event experienced in the three study sites. The situation has caused many farmers to change their planting dates for most of their crops. Although changing planting dates can be a short-term remedy to adapt to climate change, delays in planting dates due to drought can affect food security. Whiles farmers are waiting for rainfall before planting, the likelihood of available food to depend on will be a huge challenge. Pests or rodents in farms were also found as a major problem affecting farmers during climate change and when there is drought.

Respondents raised several concerns about the impact of climate change on the community. These challenges include the death of livestock, damage to crops, less food to harvest, hunger, and loss of hope to the farm are some of the effects of drought on the rural poor. In view of the above observations, it can be argued that climate change affects food security, rural poor communities. The above findings are in line with other previous studies which also found that climate change negatively impacts food security [Boko et al., 2007; Magdoff and Tokar, 2010; Intergovernmental Panel on Climate Change (IPCC), 2014]. It is important to state further that, respondents from the three study sites have the knowledge and are aware of the changes in weather patterns and the season that this weather becomes problematic to the community. This prior knowledge, if utilised well, can assist the community to build strategies before the occurrence of an extreme climate event.

It also emerged that rural households embark on different adaptation strategies to address the impact of climate change.

A significant number of respondents from the three study sites confirmed that they have changed their farming practises during extreme weather conditions. Basic knowledge of alternative farming practises is necessary for rural communities to overcome extreme weather conditions. It is therefore argued that this knowledge should be enhanced to equip farmers with alternative farming practises that can assist to build resilience against food security.

Farmers in all the three study sites also introduced new crop varieties, changed to shorter cycle crop varieties, and stopped cultivating some crop varieties. These practises are an indication that rural farmers from the study sites strive to incorporate different adaptation strategies to build resilience for climate change. The responses revealed that these adaptation strategies were implemented due to drought, rainfall variability, less rainfall, and increased temperature. The findings in the current study corroborate with Alemayehu and Bewket (2017) study which found that adaptation strategies used by smallholder farmers to manage their crops include changing planting dates, crop diversification and the use of drought-tolerant and fast-maturing crops and improved seeds. However, these adaptation strategies may be considered as a temporal solution for many households, therefore it is argued that rural communities should be assisted to develop structures and infrastructure that will contribute to long term solutions to manage extreme weather events.

Whiles authors such as Bawakyillenuo et al. (2016), and Epule et al. (2017) have recommended irrigational practises as a strategy to manage drought-related issues in rural households, it was a major concern for the researcher to establish that many of the respondents from the three study sites did not have any mechanism in place for irrigation activities in their farms. This shows the communities overreliance on rainfall for their farm produce. Given these findings, it can be argued that food security can become a huge challenge for the communities in seasons where drought extends over a longer period. It is thus important to build proactive measures to increase the capacity of the rural communities to acquire irrigational facilities for their farms. More acquisition of irrigation equipment through government support and other non-profit organisations can help reduce the challenge and impact of drought in the area.

CONCLUSIONS

Although it is widely acknowledged that CC has become a global issue, there is little empirical evidence on the impact that the rural poor have experienced, and how the rural poor have responded and adapted to ensure food security. This study examined the impact that climate change has on rural livelihoods and their adaptation response to climate change in three rural communities in Eastern Cape, South Africa. Three rural communities namely Mgugwana, Manaleni, and Ndayini in the PSJ Local Municipality served as the focus area of the investigation. Findings from the study revealed that summer is the season that CC becomes a serious problem for most rural households. Particularly this period is between December to February. During this season farmers experience drought, heatwaves, and less often flood which significantly affect food production. Many rural farmers from the study sites confirmed that climate change in the area has resulted in the death of their livestock, damaged their crops, resulted in less food to harvest, exposed most households to hunger, and rendered some farmers with no interest in farming. Considering the above research findings, it is argued that climate change significantly impacts the livelihood of rural people especially in their effort to ensure food security. The study further revealed that respondents from the three study sites have changed their farming practises, introduced new crop varieties, changed to shorter cycle crop varieties, and stopped cultivating some crop varieties to respond to extreme weather conditions. However, it became known from the study that these adaptation strategies did not help the communities to address the shortage of food experienced during extreme weather events.

It is against this background that the following recommendations are made. Firstly, the government through the department of public works, department of agriculture and fisheries should provide rural communities and rural farmers with regular engagement and education to sensitise them on possible climate change events. This education should focus on the management of drought, heatwaves, flood, and soil erosion. Secondly, the government should have a policy that will focus on building dams for rural farmers. The dam will serve as a reservoir of water for irrigation during drought. This can improve crop yield and ensure food security. Lastly, there should be a renewed management effort of adaptation strategies such as education on indigenous knowledge strategies (IKS) that should be discussed and implemented with the communities. It is recommended that the ministry of agriculture and fisheries should take the lead in this initiative.

This study has demonstrated an understanding of the impact of climate change and how rural households and farmers adapt to climate change. This study also provided useful evidence to assist the government and other stakeholders to develop policies in order to assist rural poor communities to overcome the impacts of climate change. Whiles, there are recommendations offered in this study, other possible areas of research still must be done. This study focused on only three rural communities within the PSJ local municipality in the Eastern Cape of South Africa. There should be similar studies focusing on other rural communities in the Eastern Cape of South Africa at large. To provide a dual purpose of comparison, a comparative study on urban and rural households' farmers adaptation strategies to climate change can also be initiated.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Jasper Knight. The University of Witwatersrand. The participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

LA research the entire work as part of her PhD Thesis. MS supervised the work from the beginning to the end of the study. Both authors provided critical feedback and helped shape the research, analysis and manuscript.

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Implications of Climatic Stressors on Agro-Pastoral Resources Among Mbororo Communities Along the Slopes of Kilum-Ijim Mountain, North West Region, Cameroon

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Mountains are rich in pastures and water for agro-pastoral resources and supports rain-fed farming that sustain the livelihoods of many indigenous communities. This work seeks to examine the implications of climatic variability on agro-pastoral resources (pasture land, water) and food security within the Mbororo communities. To ascertain this, 350 household questionnaires were randomly administered in four Mbororo Ardorates and in-depth interviews conducted with local authorities. Quantitative and qualitative analysis of data collected revealed that the link between climate, land and water is paramount in animal rearing and crop farming in mountains. Cattle rearing and crop farming have been the main source of livelihoods for about 90% of the Mbororos as they depend on it for food and income. Climatic perturbations characterized by frequent dry spells, rainfall anomalies and other environmental stressors predicted degrading pastoral resources and the independent variable explained the outcome variable at $R = 0.787$; $R^2 = 0.623$; $\Delta R^2 = 0.622$; $p < 0.01$. This implies that 62.3% of degradation is accounted for by environmental stressors. As such, the carrying capacity of grazing have gone above the authorized number of two cattle per hectare, leading to overgrazing and degradation. Encroachments into grazing lands by crop farmers, invasion by unproductive grass species and farmer-grazer conflicts are aggravated by climatic stressors. The Fundong council and traditional authorities of the Kom Fondom have been working together to demarcate grazing land and provide water for cattle rearing. Mbororo communities are equally diversifying their activities to ensure food availability.

Keywords: climate variability, land, water, food security, Cameroon

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INTRODUCTION

Mountains are specific ecosystems rich in pastures and water for agro-pastoral activities. These resources, coupled with specific ecological conditions have made tropical mountains attractive to Mbororo pastoralists. However, mountains are very sensitive to climatic aberrations and agro-pastoralists have been considered as one of the most climate-change-vulnerable groups on the planet (Herrero et al., 2016). Food production and livelihoods of agro-pastoralist depend on the climate, land and water nexus. Land provides the basis for livelihoods as it supplies food, fresh water and multiple other ecosystem services and biodiversity (IPCC, 2019). Pastoralism is a critical asset for food security and it sustains livelihoods in and outside of pastoralism (Krätli et al., 2020).

Climate change has led to increase in rainfall intensity, floods frequency and severity and dry spells which have exacerbated land degradation as well as other agro-pastoral resources (IPCC, 2019). Climate variability and change is hitting hard on agro-pastoral systems and making the future uncertain for pastoralists in Sub-Saharan mountains (Herrero et al., 2016). This uncertainty warrants that adaptation systems be reviewed and upgraded to lessen the negative impacts of weather aberrations. Works by Nakashima et al. (2012) and Herrero et al. (2016); show that pastoralists communities in Sub-Saharan Africa are affected by climate change, with impacts ranging from rangelands, livestock, water and extended repercussions on income and food security. Agro-pastoral systems are highly vulnerable and adapting requires multiple and simultaneous responses. According to IPCC (2014), adaptation implies adjustment to actual or expected climate to lessen the negative effects or exploit the opportunities. This is crucial as pastoral resources are already highly vulnerable.

Climate change has become a major threat to food security especially in Sub-Saharan Africa that depends on rain-fed agro-pastoral systems (FAO, 2014). Livelihoods and food security of agro-pastoralists are already negatively affected by climate change. Ensuring food production and food security in the context of global climate change necessitates an understanding of the links between climate, water and land. According to FAO (2015), food security exists 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. Climate change has compromised the ability of indigenous communities to satisfy their food needs because it has profoundly affected the conditions under which agro-pastoral activities are carried out.

As such, the achievement of Sustainable Development Goals is not possible without directly addressing the impacts of climate change. Eradicating poverty and hunger, ensuring food security, clean water and sanitation, ecosystems conservation and restoration can only be achieved by addressing climate change issues (Capitani et al., 2018; Lewis et al., 2018). Land, water, energy and climate are key inputs of the food production system. Rapid population growth, deforestation, overgrazing, over-cultivation and bush fires have exacerbated the impacts of climate change on mountain agro-pastoral systems.

In Cameroon, cattle rearing is an important economic activity. It is prominent in the Northern regions and in the North West Region where it is a source of livelihoods to more 5,041 households (Manu et al., 2014). According to Nyuymenka (2015), traditional grazing dominated and still does, with more than 95% of Mbororo Fulani practicing extensive grazing that depends solely on natural pasture.

The state of the environment has been shown to play a great role on the sustainability of cattle rearing. According to Tamufor et al. (2017), sustainable cattle herding demands adaptation to the stressful environment, the conservation of ecosystems and biodiversity. Atanga (2013), noted that soils of the region are progressively degrading due to overgrazing, invasion of pastoral lands by noxious plants and others. Consequently, the environment is becoming unsuitable for pastoral nomadism and herders are diversifying their livelihood sources. According to Pelican (2008), the Mbororo in the Cameroon Grassfields are agro-pastoralists. While most families complement cattle husbandry with subsistence agriculture, they first and foremost understand themselves as cattle pastoralists. As an adaptation to nomadic pastoral crisis, transhumance has been adopted as an alternative form of rearing by the Mbororos. They move with their cattle seasonally between uplands and lowlands in search of pasture and water. The transhumance zone was carved by Presidential Decree No. 76/420 of the 1976, regulating the movement and exploitation of livestock in the country.

The Mbororo communities of the Kilum-Ijim mountain range have adopted a sedentary lifestyle. They have structured communities called Ardorates. However, they still have many challenges. The question of access to land resources by recently sedentarized pastoralists is a difficult one because their settlement is not only facilitated by available space; but most importantly by the attitude of native people (Ngalim, 2015). Climate variability and change have equally contributed in degrading their already fragile systems and increasing food insecurity. Many studies have singled out climate change as a crucial factor affecting agro-pastoral systems without establishing the nexus existing between climate and pastoral resources of land and water. This work thus makes a useful contribution in the understanding of the relationship that exists between land, water and food security in the context of global climate change.

MATERIALS AND METHODS

The Study Area

This study is carried out along the western flanks of the Kilum-Ijim Mountain range where pastoral activities are prominent. It falls precisely in the Fundong Subdivision, located between latitude 6°7′ and 6°24′ North of the Equator and between latitude 10°41′ and 10°31′ East of the Greenwich Meridian. It is bounded in the East by the Chiefdoms of Oku, Babanki and Babungo to the South, Bafemen to the North, Beba-Befang to the North-West and Bafut in the West. Prominent here is Mount Oku (3,011 m) which is the highest point along the Kilum Ijim range (**Figure 1**). The land covers total surface area of 1,592 km² comprising the Kom, the Bums and Mbororo or Fulani community with a population estimated at 45,831 inhabitants (BUCREP, 2005). The settlement of Mbororos amongst these native communities have been received with mixed feelings. They occupied hilly slopes and other marginal lands whose agricultural productivity was low. This exposes them to risks of environmental degradation, including climate change.

On the temporal scale, this work covers the period from 1960 till present. The year 1960 marked the beginning of actual sedentarization of a majority of the Nomadic Mbororo pastoralist in this area. The sedentarization was accompanied by a diversification of activities and a change from pastoral to agro-pastoral activities. They contributed significantly in supplying food to their communities and to the native communities. Nevertheless, this change in activities reduced their chances of using traditional knowledge systems to produce food and cope with the changing climate. Limited access to resources such

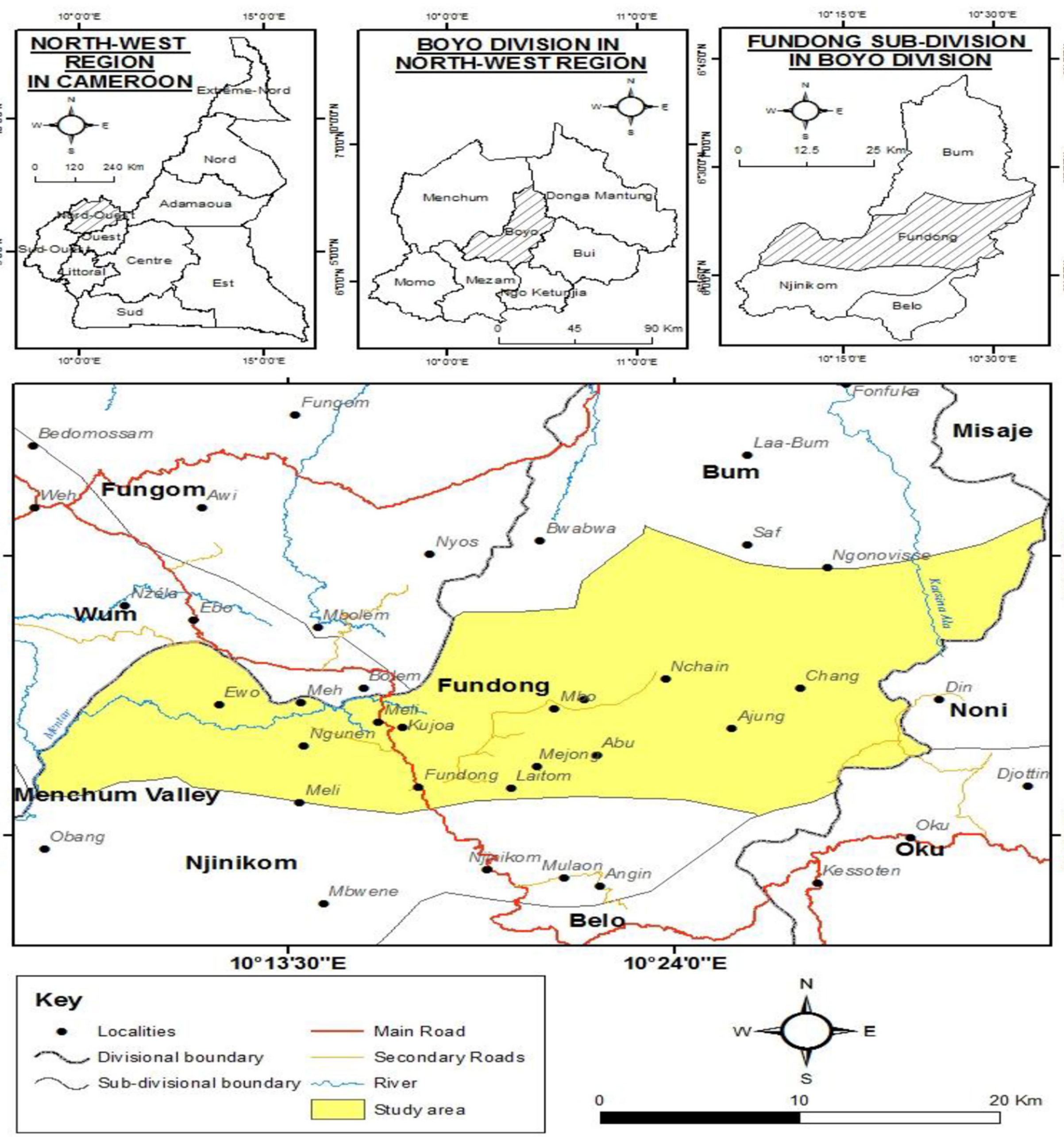

FIGURE 1 | The study area.

as land and water and discrimination suffered by Mbororos from the native populations have given rise to what was termed "the Mbororo problem" in the North West region of Cameroon. Given that climate change adaptation demands equitable distribution of natural resources, it was thus interesting to study food production systems within these resource-poor communities, the impacts of climate variability on the already stressed resources and the coping options implemented across households and institutions.

Methods of Data Collection and Analysis

This study adopted a cross sectional approach in data collection. Qualitative and quantitative data was collected from primary and secondary sources. Primary data was collected using questionnaires and interviews. Using a simple random sampling technique, the sample was computed at 95% confidence level, with a 0.05% error margin using the formula;

$$n = N^*[Z^{2*}p^*(1-p)/e^2]/[N--1+(Z^{2*}p^*(1-p)/e^2)] \quad (1)$$

TABLE 1 | Distribution of questionnaires in villages.

Villages	Number Households	Number of Questionnaires	Percentages
Mentang 2 Ardorate	800	35	10%
Meli	500	20	5.7%
Mbam 1	300	15	4.2%
Mbam 2	350	20	5.7%
Mentang 1 Ardorate	900	35	10%
Bolam	450	26	7.4%
Aduck	420	25	7.1%
Ijim 1	500	20	5.7%
Ijim 2	350	15	4.2%
Achian	850	34	9.7%
Fundong Center	730	30	8.6%
Fujua	400	30	8.6%
Ngwah	300	15	4.2%
Anchangne	650	30	8.6%
Total	7500	350	100%

Source: Fieldwork (2019).

where; N = Population size, Z = Critical value of the normal distribution at the required confidence level, p = Sample proportion, e = Margin of error.

This computation gave an adjusted sample size of 350 households. Questionnaires were administered randomly in 14 villages (**Table 1**). The number administered in each village varied proportionally with the number of households. The use of a household questionnaire permitted to get data from pastoralist since there is no official data base and equally appreciate practices carried out at individual levels.

Table 1 shows that the number of questionnaires per village was proportionate to the number of Mbororo households in each village. The highest numbers were administered in Fundong Center (8.6%), the Ardorates of Mentang 1 and 2 (10%), Fujua and Anchange (8.6%). Interviews were conducted with the Ardos of Mentang 1 and 2, Ardos of Ijim 1 and 2 and that of Achian. The Divisional Delegate of Livestock for Fundong, the Mayor for Fundong Council and some quarters heads. These provided information that could not be gotten through questionnaires. Field visits were carried out during periods marking important activities that affect pastoral life such as transhumance period, beginning of rainy season, beginning of crop farming. These periodic visits permitted us to take photographs of some activities, see state of infrastructures and appreciate the difficulties encountered by pastoralists. Archives of the Fundong Council and MOSCUDA Archives were consulted. *In-situ* climatic data was collected from Divisional Delegation of Agriculture and rural Development.

Data collected was treated and analyzed quantitatively and qualitatively. Questionnaires were treated in SPSS while interviews were treated using thematic and content analysis. Climate data set was smoothened using five-year moving averages in order to correct extremes and reduce observation errors. Variability was computed using coefficient of variations (CV) while climatic variability trends were established using rainfall anomaly index. Interviews were transcribed and analyzed using thematic and content analysis. The relationship between environmental factors and pastoral resources was established using a linear regression function and coefficient of determinations to get the proportion of other variables (human factors). Environmental factors were entered as a predictor of degrading pastoral resources and the independent variable used to explain the outcome variable.

PRESENTATION OF RESULTS AND ANALYSIS

Identification of Climatic and Non-climatic Stressors on the Agro-Pastoral System

Fundong Subdivision is located in the Western Highlands of Cameroon with a humid tropical climate. It has two main seasons, a long rainy season (8 months, from mid-march to mid-November and short dry season that lasts for 4 months). Seasons are regulated by the shifting of the Inter-Tropical Convergence Zone (ITCZ) due to trade winds. Generally, the region receives heavy rainfall ranging from 2,000 to 2,500 mm per annum. The great variations in slope has put in place a mountain climate conducive for pasture growth and for the cultivation of market garden crops.

Daily temperatures range from 15°c to 38°c with an annual average temperature of about 20°c. The mountain slopes are generally cold, windy and wet. The presence of the Kilum-Ijim mountain range has equally led to temperature modifications as there is a systematic reduction in temperatures as we ascend the mountain slopes. This cool climatic conditions have made the area free from tse-tse flies, thus favoring cattle breeding. However, climate variability and change are compromising this comparative advantage.

Climate variability in this area is characterized by a coefficient of variation (CV) of 14% for mean annual temperatures and 21% for annual rainfall amounts. These CV values are below the threshold of 30% for tropical regions and shows that rainfall and temperature are reliable for agro-pastoral activities. However, corresponding trends indicate that global temperatures are rising while rainfall has been reducing over the last few decades. Significant anomalous scenarios have been established over the time series and data sets (**Figures 2**, **3**).

Temperatures have been rising with positive and negative anomalies ranging from +0.5°C and −0.4°C, around the annual mean of 26.24°c. In the same light, rainfall have been fluctuating significantly around the mean annual amount of 1969.226 mm. Positive anomalies go up to +300 mm while negative anomalies go beyond −320 mm. Positive anomalies signify periods of more water supply while negative anomalies are periods of water shortages. The frequency and intensity of extreme events, especially dry spells have been exacerbated. These climatic aberrations have compromised the reliability nature of rainfall with implications on water and pastures.

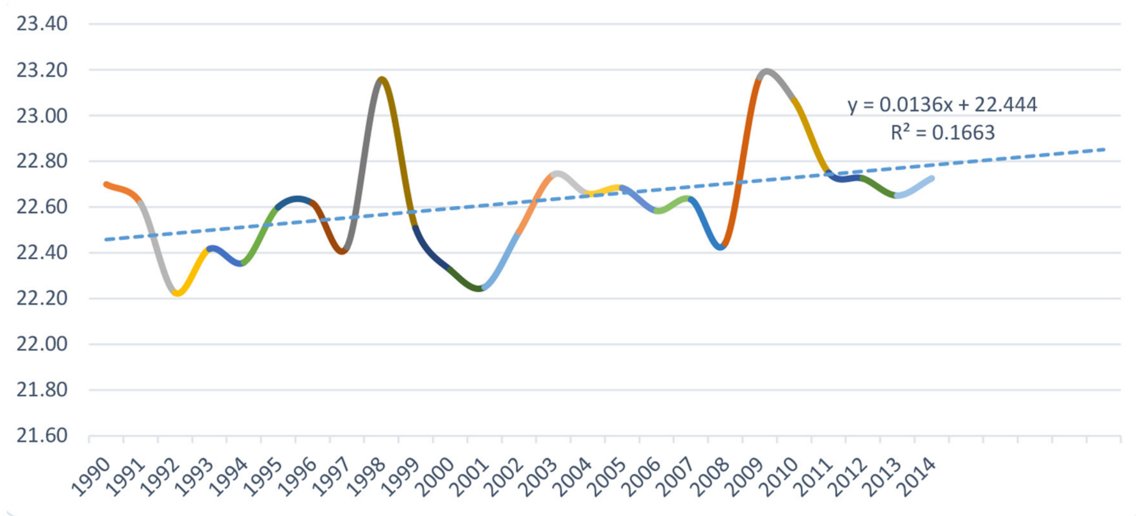

FIGURE 2 | Observed temperature trend and anomalies in Fundong.

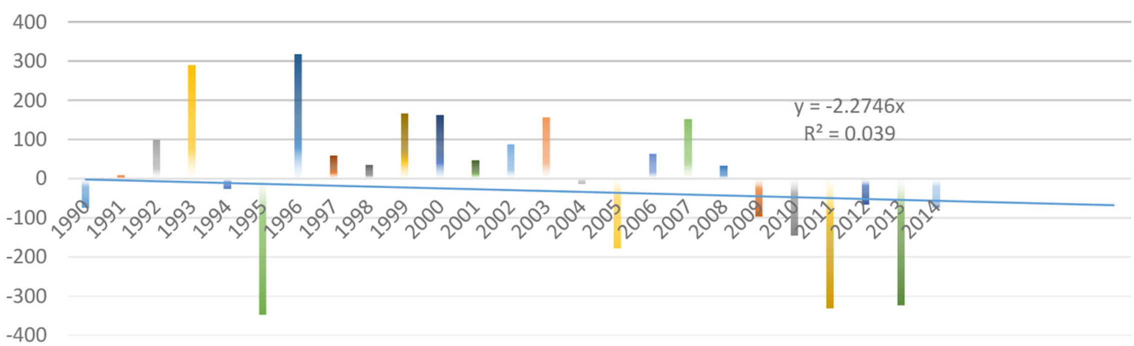

FIGURE 3 | Observed Rainfall trend and anomalies in Fundong. Source: DDARD for Fundong (2018).

Reduction in Grazing Land and Overgrazing

A greater proportion of rearers in this area use the traditional method of cattle grazing which is characterized by overgrazing and pasture degradation. The natural pasture lands are rapidly reducing in quality and quantity while the cattle population is on the rise. This has resulted to over concentration of cattle over the reducing grassland, which is already affected by climate change and other anthropogenic factors. The first cause of this overgrazing is attributed to an increase in cattle population without a corresponding increase in grazing land (**Figure 4**).

Figure 4 shows that the cattle population have been increasing steadily from 2013 to 2017 in the main grazing zones or Ardorates of Ijim, Achian, Metang I and Metang II. The implications of such an increase on pastoral resources are seen when we evaluate the carrying capacity of each grazing zone. The computation of the carrying capacity shows that with the present scenario, the carrying capacity of grazing lands have been superseded, leading to pasture degradation, both in quality and quantity.

Considering, the relationship between cattle numbers and grazing zones, the cattle density have been determined for each grazing zone (**Table 2**).

Table 1 shows that cattle densities or carrying capacities varies from one zone to the other. The differences are obvious because the surface areas and the cattle populations are not the same. According to the Divisional Delegation of Livestocks, Fisheries and Animal Husbandry, the normal carrying capacity for Fundong area is two cattle per hectare of grazing land. However, statistics from the table above shows that some grazing zones had more than their carrying capacity (**Figure 5**).

Figure 5 depicts that two zones, Ijim and Metang II have carrying capacities above the authorized number of two cattle per hectare. The implications of this is that the pasture lands are degrading rapidly as well as other resources such as water. Equally, as the number of cattle population increases, there is a corresponding increase pressure on land and resources resulting to overgrazing and the acceleration of conflict between the

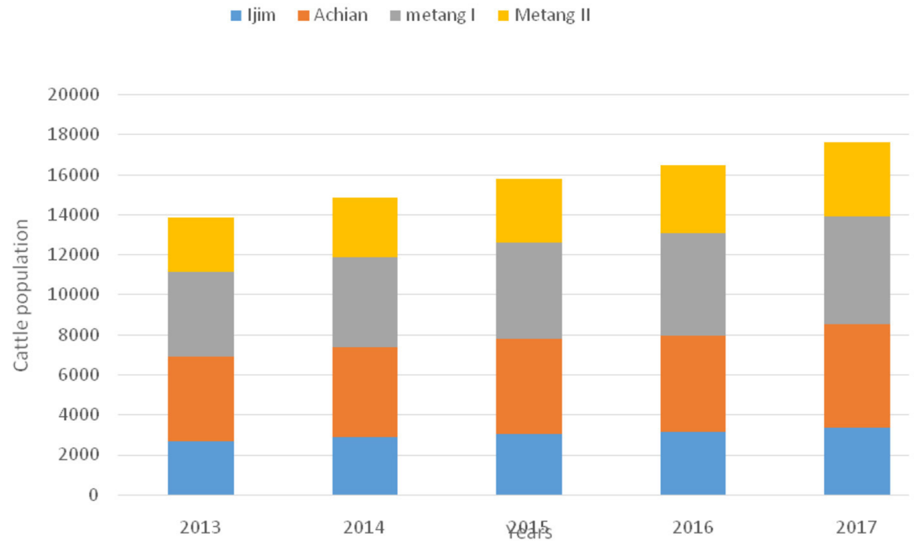

FIGURE 4 | Evolution in cattle population in the main grazing zones. Source: Generated from Field Data (2020).

pastoralists themselves and the agriculturalist on the other hand because of the reduction in surface land and infertility of the soil.

Pasture Degradation and Shrinking Water Courses

Mbororo pastoralists along the Kilum Ijim slopes depend on natural pasture to feed their cattle. The growth of pasture on the dry and hilly slopes is conditioned by the onset and duration of the rainy season. However, field surveys demonstrated that the sporadic and unreliable rainfall pattern, with increasing frequency of dry spells have negatively affected the growth of pasture. The quantity and quality of pastures have been reducing over the years, forcing herders to move over long distances in search of fresh pasture or go on transhumance. **Figure 6** shows the poor pasture quality in the grazing zones and a shrinking river course.

In **Figure 6A** shows a completely dry landscape with poor pastures. Cattle cannot feed properly on such grazing lands and given that their carrying capacities have been exceeded, the landscape is gradually being transformed into a bear and unproductive area. **Figure 6B** on the other hand shows a shrinking river course. Cattle have to go into the river bed to be able to drink water. Amongst the factors responsible for such rapid degradation is climate change as ascertain by Mr Ali in the following excerpt.

> "....some years back, we use to have fresh grass allover and enough water to feed our animals. We do not understand what is happening any more, the sun has become too intense and rainfall has reduced. The grazing lands have become drier because there is no rain water to make pastures grow normally. Some fields in Achain have completely dried off and grass do not grow on it any longer. Cattle drink a lot of water on daily basis, now that rivers are drying due to too much sun too, our activity will be affected badly...."

This excerpt captured from a discussion with a herder in Fundong testifies the perceptions of the Mbororos on the effects of climate change on pasture lands. The degradation of pastures which is attributed equally to overgrazing has been exacerbated by rainfall irregularities and dry spells. The consequences of this have been the drying up of pasture lands and a reduction in grazing zones. The dependence of Mbororo pastoralists on natural pastures have limited their coping options as transhumance corridors are equally affected. The conquest for new grazing zones have resulted to encroachment into farming zones, causing agro-pastoral conflicts. The outcome has been a fall in cattle and milk production and food insecurity.

Encroachments Into Grazing Zones and Farmer-Herder Conflicts

The native Kom population are mostly crop farmers with only a few involved in cattle rearing. The fast growing native population and the desire to increase food production have led to the expansion of farms into mountain slopes and into grazing lands. The cold mountain climate favors the cultivation of market gardening crops such as Irish potatoes and vegetables. As such areas that were meant for cattle rearing have entered into competition with crop farming (**Figure 6D**).

Figure 6D depicts the encroachment of farms into grazing lands. These farms are mostly owned by the native population who usually discriminate against the minority Mbororos especially on land ownership. The portions of the grazing zones scrambled over by farmers are usually the lowlying zones with fertile soils that supports pasture growth. In such scenarios, the Mbororo herders are forced to carry their cattle to the hilly slopes with less pasture and a rugged terrain that makes cattle movement difficult. The agro-pastoral code is not respected in this area which is gradually becoming a mixed farming zone. The Mbororos themselves are getting sedentarized in Fundong

TABLE 2 | Determining carrying capacity per grazing zones.

Ijim ardorate					
years	2013	2014	2015	2016	2017
cattle population	2668	2855	3014	3160	3340
grazing land	878.6	878.6	878.6	878.6	879.6
cattle density	3	3	3	4	4
average density	3.42 cattle/hactare				
Achian ardorate					
years	2013	2014	2015	2016	2017
cattle population	4241	4543	4771	4980	5172
grazing land	3953.9	3953.9	3953.9	3953.9	3953.9
cattle density	1	1	1	1	1
average density	1.2 cattle/hactare				
Metang i ardorate					
years	2013	2014	2015	2016	2017
cattle population	4237	4494	4810	5143	5434
grazing land	2635.7	2635.7	2635.7	2635.7	2635.7
cattle density	2	2	2	2	2
average density	1.83 cattle/hactare				
Metang ii ardorate					
years	2013	2014	2015	2016	2017
cattle population	2749	2976	3211	3434	3672
grazing land	1317.9	1317.9	1317.9	1317.9	1317.9
cattle density	2	2	2	3	3
average density	2.44 cattle/hactare				
I1im ardorate					
years	2013	2014	2015	2016	2017
cattle population	2668	2855	3014	3160	3340
grazing land	878.6	878.6	878.6	878.6	879.6
cattle density	3	3	3	4	4
average density	3.42 cattle/hactare				
Achian ardorate					
years	2013	2014	2015	2016	2017
cattle population	4241	4543	4771	4980	5172
grazing land	3953.9	3953.9	3953.9	3953.9	3953.9
cattle density	1	1	1	1	1
average density	1.2 cattle/hactare				
Metang i ardorate					
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grazing land	2635.7	2635.7	2635.7	2635.7	2635.7
cattle density	2	2	2	2	2
average density	1.83 cattle/hactare				
Metang ii ardorate					
years	2013	2014	2015	2016	2017
cattle population	2749	2976	3211	3434	3672
grazing land	1317.9	1317.9	1317.9	1317.9	1317.9
cattle density	2	2	2	3	3
average density	2.44 cattle/hactare				

Source: Computed from Field Data (2020).

with well-structured and organized traditional systems called the Ardorats. A good of them have equally adopted crop cultivation as a means of livelihoods.

The effects of encroachment into grazing lands have been a source of frequent conflicts between rearers and crop farmers. Cattle in search for pasture and water gets into farms and destroy crops and the reaction of farmers toward such destruction have been violent in some cases. Although there is an agro-pastoral commission in MBOSCUDA that work together to ensure a peaceful resolution of conflicts between farmers and herders, the situation on the field is still deplorable. Many attacks of the local population on cattle have been reported and many court cases are on-going. In an interview with Mr Aliyu, a Mbororo youth leader, he had the following to say;

> "……land acquisition and ownership is a serious problem with us. Our parents have been settled here for many years but they still consider us as strangers. The native population feel they have more rights over grazing land than us….."

This excerpt raises the problem of land management and governance. The system of land acquisition and distribution in Fundong Subdivision reflects the land tenure system of the Western Highland which is an indicative of the customs of the people. The tenure system in the entire Kom Highlands gives ownership of land to the Fon. The Fon's titular ownership of land is recognized and expressed in a number of ways. The land could be donated to a stranger by the village or lineage head but with the approval of the Fon. Grazing land was to be demarcated and left at the disposal of the Fulani cattle graziers, under the control of the Ardos (the Mbororo traditional ruler) by the Fon and the administrative authorities. The Ardos could then distribute the land to other herders. However, many Mbororos still feel discriminated upon as far as this traditional tenure system is concerned.

IMPLICATIONS OF ENVIRONMENTAL STRESSORS ON AGRO-PASTORAL RESOURCES AND FOOD PRODUCTION

The Regression Model

The relationship between climatic stressors and agro-pastoral resources was determined using a regression function and the model summary has been presented on **Table 2**:

From **Table 3**, environmental factors were entered as a predictor of degrading pastoral resources and the independent variable explained the outcome variable at $R = 0.787$; $R^2 = 0.623$; $\Delta R^2 = 0.622$; $p < 0.01$. From the analysis it is evident that

TABLE 3 | Predicting sedentary tendency among Mbororo Nomads.

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics					Durbin-Watson
					RSquare Change	F Change	df1	df2	Sig. F Change	
1	0.789[a]	0.623	0.622	5.41092	0.623	359.05	1	217	0.000	1.720

[a] *Predictors: (Constant), Environmental stressors.*
[b] *Dependent Variable, agro-pastoral resources.*

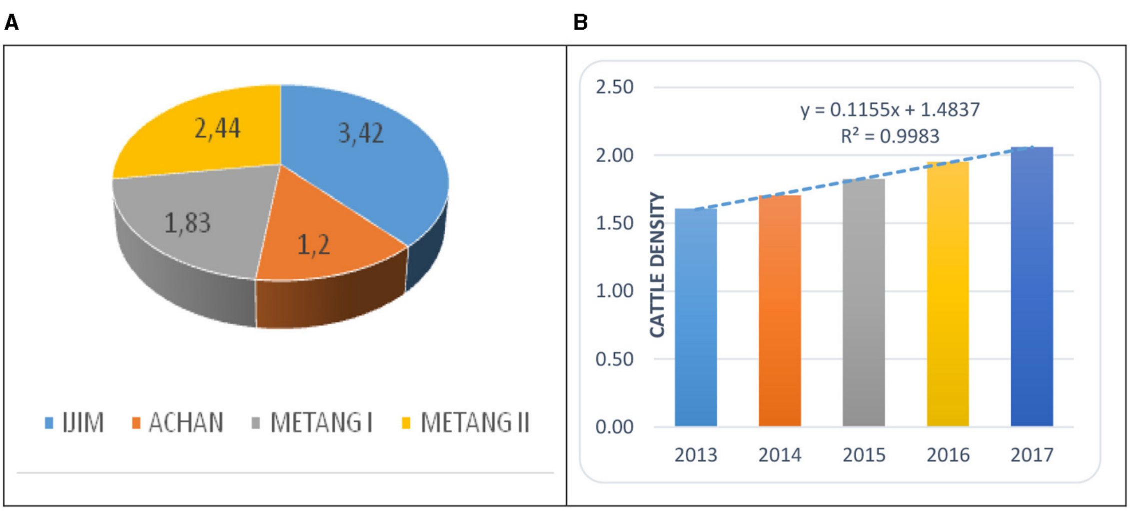

FIGURE 5 | Variation in carrying capacity in space and time. **(A)** Variation in carrying capacities within grazing zones. **(B)** Evolution in carrying capacities over the years for the entire zone. Source: Generated from data in **Table 2** (2020).

FIGURE 6 | (A,B) Pasture and rangeland degradation. **(C)** Shrinking river course. **(D)** Encroaching of crop farming into grazing lands. Source: Umaru (2018).

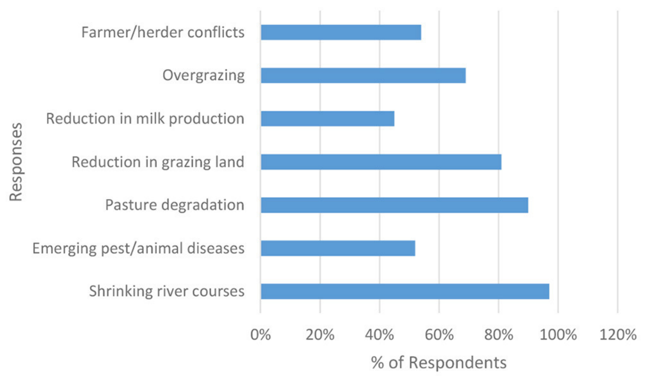

FIGURE 7 | Observed Impacts of climate variability on pastoral resources. Source: Compiled from Fieldwork Data (2020).

environmental stressors, including climate change were able to predict 62.3% of the variation in the independent variable.

This implies that climatic stressors, including climate variability and change could predict the changes in pastoral resources at 62.3%. This corroborates with herders observations as they identified a number of observable landmark consequences on the rangeland. Though at different degrees, the impacts are related to pasture degradation and water shortages with associated impacts (**Figure 7**).

From **Figure 7**, pastoralists were unanimous to the fact that river courses are shrinking and affecting water demands for cattle (97%) while pasture degradation to environmental and human stressors was acknowledged by 86% of the study population. The dependence of pastoralists on natural and shrinking water sources have led to congestion and conflicts amongst herders. The warming climatic conditions upslope have favored the emergence of animal pests and diseases. Despite possibilities to constantly vaccinate cattle and treat grazing lands, the costs are very high and the already resource-poor population cannot afford.

Implications of Environmental Stressors on Livelihood Sources and Food Production

Climate change has been shown to have affected the natural resource base for the production of food and provision of income in the Mbororo communities. The performance of agro-pastoral systems is determined by the availability of land, water and energy, which are already hit hard by climatic aberrations. The following excerpt shows the weight of climate change on food production and social systems;

> "……..we depend on cattle rearing to feed our families. For the past 5 years, my cattle have been reducing because grazing land is reducing too. It is difficult for me to feed my family and my two sons have gone to Bamenda town to look for jobs. I told them that cattle rearing alone could no longer satisfy our needs….."

This excerpt from an interview with Mr Ibrahim, a family head and a pastoralists clearly demonstrates the inability of pastoral systems to ensure a steady food supply within the context of climate change. It is evident that the sustainability of their livelihoods entails a livelihood diversification as land is inelastic. Food security entails not only quantity but quality as well. The shrinking water sources get constantly polluted, the poor quality of pasture, the long distance movements to get pasture have reduced the quality of cattle products.

Findings equally revealed that thunder storms and lighting have increased in frequency with drastic consequence on the rearing of animals especially cattle. Each year especially during sudden and short-duration intensive rainfall accompanied by thunder and lightning, animals especially cattle and horses are killed. This have become frequent on the slopes of Kilum Ijim and herders attributes it to the changing rainfall pattern. It should be noted that the primary source of Mbororo income is the sale of animal and their products such as milk, butter and meat. The dependence on cattle for food and income has made the dependency ratio very high. The Mbororo culture does not allow women to take formal jobs and this has limited their ability to contribute in sustaining their families.

Women and children concentrate on animal milking and the sale of products such as butter. The reduction in grazing land and in cattle population has seriously led to a reduction in milk production which is an important sources of food for the Mbororos. It was revealed that the purchasing power of the Mbororo is reducing significantly but the numbers of persons to feed are increasing rapidly. The reduction in cattle heads due to fast rate of reduction on grazing land, climate change, and animal diseases are responsible for food insecurity within the Mbororo communities.

The adoption of an alliance system of farming introduced by MBOSCUDA has permitted Mbororo women to embark on crop cultivation. They cultivate maize, beans, Irish potatoes and vegetables for home consumption and for the market. Nevertheless, this activity have not yet yielded the required fruits as land ownership is a problem. Climate change especially rainfall variability has disrupted the cropping calendar and led to many crop failures in the area. The Mbororos equally lack entrepreneur skills to diversify their livelihood sources and this has led to food insecurity and poor diets.

MEASURES TO CURB THE EFFECTS OF CLIMATE VARIABILITY ON PASTORAL RESOURCES AND IMPROVE FOOD PRODUCTION

Efforts have been by the local authorities and the Mbororo community in Fundong to improve on the management of agro-pastoral resources (water and land) in the context of climate change.

Rangeland and Pasture Management

Adaptation to climate variability and change requires proper land management systems and good governance. Cattle rearing and rangeland management in Cameroon are regulated mainly by Decree No 76/420 of 14 September 1976, modified by Decree

No 86/755 24 of June 1986. According to Articles 1 and 2 of Decree No 76/420, animal grazing is free on all grazing land of the Country, but the Minister of livestock can limit grazing in some specified grazing land especially in case of a disease outbreak. There are also laws regulating pastoral resources with the primary issue in considering changes toward individuated tenure being equity, not efficiency. Questions such as how should "land" be divided among pastoralists (groups of pastoralists), or between pastoralists and non-pastoralists? are tackled.

Farming and grazing lands are managed by the land consultative board and the agro-pastoral commission. The agro-pastoral commission allocates and demarcates farmlands and grazing lands in rural areas according to the needs of the population as well as development needs, defines conditions for the use of a mixed farming zone, examines and settles farmer-herder conflicts. However, the functioning of this commission has problems. Mbororos are underrepresented and discriminated upon when critical decisions are being taken. This has kept them in a minority situation thereby limiting their efforts in climate change adaptation.

In the domain of pasture management, pastoralists have adopted alternative and environmentally friendly methods of rearing. Transhumant pastoralism which is widely practiced in the area has considerably reduced the rate of rangeland and pasture degradation. Modern methods of rearing such as ranching have been introduced in the area and adopted by herders. For instance, paddocking form of rearing and the planting of improved pasture species have been introduced in the Mentang1 Ardorat (**Figure 8**).

Field investigations revealed that apart from climate change adaptation, the disadvantages of a nomadic lifestyle coupled with the important role played by NGOs and MBOSCUDA in this area have encouraged many herders to adopt ranching as a method of rearing. Herders reported that this method has increased the rate of pasture degradation and improved on the quality of cattle and milk produced. The improved grazing land have a high carrying capacity as many animals can be fed over a small surface area of grazing land. The advantage of these grazing land is that they are used during periods of pasture shortages and also, during transhumance. The young cattle or the ones that are not able to move over long distances are grazed on these planted pasture fields. The animals can stay and feed here for a period of over two months. The effects of dry spells are less felt by such improved pasture species.

Improved Water Management

Water is one of most important pastoral resources that is vulnerable to the vagaries of weather. The failure of rain-fed systems due to climate variability and change have negatively affected food production. Mbororo communities depended on shrinking streams and natural sources for potable water and for water to feed their animals. Recently, efforts have been made by MBOSCUDA and the Fundong council in order to provide these facilities to the people (**Figure 9**).

As established earlier, climate variability and change have led to a reduction in water resources. Improving water supply is an important element of climate change adaptation in nomadic communities all over the Fundong Subdivision. With water shortages, herders moved over long distances in search for water and pasture, especially in the dry season. Now, the availability of these water points have reduced movements and encouraged production during water stressed periods. Field surveys revealed that most of these water supply points are treated by the veterinary services, making them void of animal diseases.

DISCUSSIONS

Climate Change, Land, Water and Food Production Nexus

> "…….climate change creates additional stresses on land, exacerbating existing risks to livelihoods, biodiversity, human and ecosystem health, infrastructure, and food systems (high confidence). Some regions will face higher risks, while some regions will face risks previously not anticipated (high confidence). Cascading risks with impacts on multiple systems and sectors also vary across regions (high confidence)……" IPCC, 2019

This extraction from the IPCC (2019) special report on climate change, desertification, land degradation, sustainable land management, food security and greenhouse gas fluxes in terrestrial ecosystems stands tall to demonstrate the effects of climate change on land and food production systems. Land is an indispensable resource for food production by agro-pastoral systems and its inelastic nature has made it vulnerable to degradation with a lot of risks associated. The Mbororo pastoral communities along the Kilum Ijim mountain slopes live in a fragile ecosystems and climate variability and change have increased the stress on pastures and increased the risks on their food production systems and incomes.

Rangeland and pasture degradation in the grazing fields of Fundong are attributed to increasing population pressure and overgrazing. The carrying capacities of grazing zones are exceeded leading to greater risks. This work has pointed out the fact that the rapid degradation of pasture lands have led to a fall in cattle production. The land crisis among the Mbororo communities who already feel discriminated upon have exacerbated the impacts resulting from the vagaries of weather. Rainfall has become unreliable and the frequency and intensity of dry spells are increasing with marked repercussions on food production systems. These findings corroborates with the works of Lemma et al. (2013), Herrero et al. (2016) and Krätli et al. (2020).

According to FAO (2014), climate variability and change have reduced the productivity of farm lands thereby affecting small scale farmers negatively. The intensity of risks associated to land degradation to climate change have been aggravated by population pressure on already stressed resources as well

FIGURE 8 | Ranching and improved pastures in Mentang 1 Ardorat. **(A)** Ranching in Mentang. **(B)** Cultivated improved pasture species. Source: Umaru (2018).

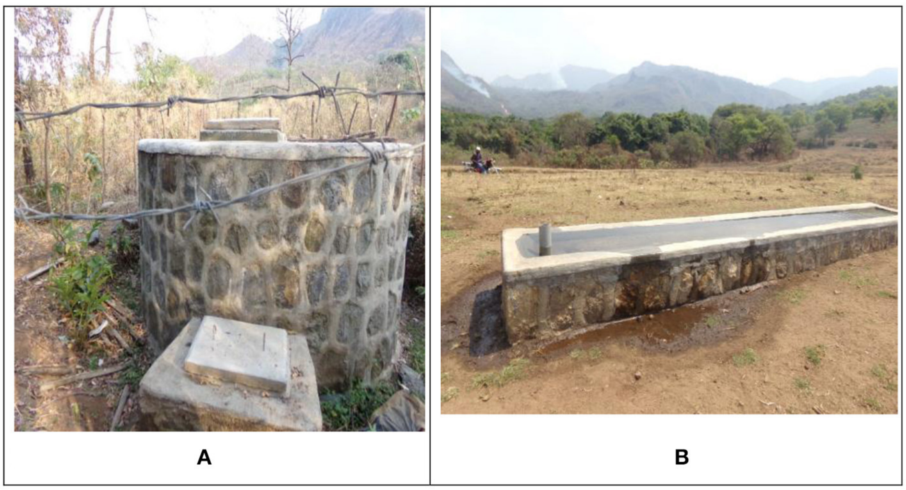

FIGURE 9 | Water supply for livestock production in Achain Ardorat. **(A)** Water reservoir(tank). **(B)** Cattle drinking point. Source: Umaru (2018).

as the low adaptive capacities of farmers (IPCC, 2019). Pastoralists of the Kilum Ijim Mountain have less adaptation options and limited access to land. Their over-dependence on cattle rearing have made them vulnerable to risks of foods shortages as their source of livelihood is threatened by the impacts of climate change. Land availability is necessary for proper adaptation and it is revealed that climate change driven land degradation has led to a fall in food crop production, meat, milk and butter which are the main stay of agro-pastoralists communities.

Agro-pastoral systems in the Western highlands of Cameroon in general are rain-fed. The productivity of land depends on the availability of water, either for plant (pasture) growth or for livestock. Water for crop production and pasture growth comes from rainfall while livestock drink water from rain-fed streams. It has been established that streams and natural water sources have been shrinking due to rainfall variability and dry spells. Recently, herders have been moving over long distances to get water for their animals with a lot of risk. Attacks by tse-tse flies, cattle theft, conflicts between herders over water sources are some of the problems resulting from long distant search for water sources. The consequence has been a reduction in the quality of products and a general fall in food production. Many studies have reported food insecurity among pastoralists such as FAO (2014, 2015) and Capitani et al. (2018).

Climate driven land degradation and water scarcity have increased the risk of food insecurity.

> "…..Food security exists 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….." FAO (2018)

Climate variability and change have reduced the ability of communities to be food secured. It is established that the achievement of sustainable development goals and the fight against poverty and hunger cannot be effective without a proper climate change adaptation strategy. This work thus contributes in revealing the state of exposure to the risk of poverty and hunger within a minority community with limited access to pastoral resources of land and water.

Land and Water Management for Pastoral Resources

Pastoralists and stakeholders in the agro-pastoral sector of the Western Highlands of Cameroon have been making efforts to ensure the sustainable management of agro-pastoral resources (Azuhnwi et al., 2017). The increasing population and rising pressure on diminishing resources have prompted autonomous and planned actions. Along the Kilum Ijim Mountain slopes, more the 70% of Mbororo communities have adopted transhumant pastoralism as means of cattle rearing so as to reduce pressure on pasture lands. Another lesser majority carry out ranching and planting of improved pasture species to supplement the natural pastures. These efforts have been carried out by other pastoralists' communities in Africa as reported by Eriksen et al. (2011) and Aida et al. (2018). For water resources, the Fundong council have provided potable water to Mbororo communities. Cattle water drinking points have been constructed in some Ardorats such as Achain and this has reduced pressure on natural sources. Intervention of NGOs such as HIEFER International and MBOSCUDA have been accompanying the Mbororo communities in their efforts to improve on their livelihoods.

The Cameroon legislature is sound and clear on issues regarding the management of farming and grazing lands. The presidential Decree No 76/420 of 14 September 1976, modified by Decree No 86/755 24 June 1986 provides for the formation of a pastoral commission in each grazing area that ensures the allocation and management of land and the settlement of farmer-herder conflicts. Nevertheless, the Mbororos still suffer from discrimination and under-representation in such commissions (Pelican, 2012; Jabiru, 2017). In Fundong Subdivision, the traditional tenure system still dominates where the Fon of Kom has the full ownership of land. Land is given to the Mbororo communities through their Ardos who then redistribute to rearers. Despite efforts put in the domain of land management, Mbroro communities are not yet fully implicated in the management of pastoral resources and this has curbed their abilities to adapt and mitigate the efforts of climate change and environmental degradation. According to Nformi (2008), the capacity to adapt to new circumstances is very important to minority social groups if they must continue to survive. In the same light, Pelican (2008) opined that the patterns of interest within a particular social group continually evolve due to changing conditions, such as population pressure and the value of resources, so too would the customs and practices in relation to how the resources are managed have to evolve.

Conclusions and Perspectives

This work set out to examine the link between climate change, land, water and food production within the Mbororo pastoralist communities in Fundong, situated along the slopes of the Kilum Ijim mountain range. The analysis of climatic data indicated that rainfall has been fluctuating over time series but a decreasing trend while temperatures have been rising steadily over the last few decades. Pastoralists have reported an increased frequency of dry spells with greater negative anomalies in the rainy season. This climatic perturbations have exacerbated the degradation of land and pastures as well as the shrinking of water courses. Given that agro-pastoral systems in this area are rain-fed, production have been falling, affecting the livelihoods of the Mbororos negatively. Income sources and food supply systems are already compromised by climate change and environmental degradation because adaptation is limited. Faced with increasing food insecurity, efforts have been made the domain of land management and the provision of water to grazing zones. Nevertheless, this work has proven that more needs to be done. The Mbororos are still considered as strangers and discriminated upon by natives as far as land is concerned. It is common to hear natives say "*…should a Mbororo own land in the same way they own cattle….?.*" Such statements portray the level of discrimination in a resource-degrading context which has prevented the Mbororos from adapting properly to the effects of climate change and ensuring a steady food supply system. The productivity of agro-pastoral systems requires an equitable distribution of pastoral resources and a good rangeland governance systems (Getachew et al., 2014). Cameroon has very good laws regulating the distribution and use of pastoral resources but their applicability needs to be improved upon. The bottom-top approach should be employed, the aspirations and capacities of Mbororos taken into consideration, climate change policies downscaled and incorporated into resource management systems and implementation and follow-up pastoral programs be upgraded.

Findings have shown that food security has a link with the production system in place. The agro-pastoral system includes the multiple environmental, socioeconomic and political elements that shape and are shaped by food production. Environmental stressors predicted degrading pastoral resources and the independent variable explained the outcome variable at $R = 0.787$; $R^2 = 0.\ 623$; $\Delta R^2 = 0.622$; $p < 0.01$. This implies that 62.3% of degradation is accounted for by environmental stressors. These elements, though with different intensity, work in interaction and understanding the impacts of climate change on pastoral resources require a collaborative approach. Local authorities in Fundong need to make provision for grazing land for the resource-poor Mbororo communities. Land tenure and ownership, including large land acquisitions (land grabbing) by Mbororo elites should be probe into and checked. Adaptation to climate change needs a well-structured resource base system and collaboration amongst actors. It is recommended that farmers, grazers, agricultural technology developers and climate scientists, local administrative and traditional authorities should work in a participatory way. This will help them to co-develop locally-appropriate climate-sensitive methods, build resilience and improve on food production. Further research should look at stakeholder participation, opportunities and constraints for effective management of resources within the context of climate change.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary materials, further inquiries can be directed to the corresponding author/s.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements. Written informed consent was not obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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Climate Change in Fisheries and Aquaculture: Analysis of the Impact Caused by Idai and Kenneth Cyclones in Mozambique

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Fisheries and Aquaculture are among the most popular activities in coastal regions of the world. In addition, both correspond to high-risk activities within a climate change context as they are vulnerable to environmental changes that threaten the socio-economic sustainability of the fishing communities that depend on fish for food security and income generation. In 2019, the central part of Mozambique was hit by two unprecedented cyclones: Idai and Kenneth that killed over 600 people and left nearly 2.2 million people in need of urgent assistance. The aim of the present study was to investigate the impacts these cyclones had on fisheries and aquaculture in the provinces of Sofala and Zambézia in Mozambique. The study further seeks to propose strategies that could be adopted by the communities to minimize the risks in the future. For the construction of the database, both secondary and primary data collection approaches were used to characterize the cyclone events. Secondary data was collected through sector reports and previously published articles, while primary data was collected through interviews with fishers, sector employees, and aquaculture producers in the affected provinces. The results revealed that these natural events had both a direct and indirect impact on fishing, as they affected more than 1,440 fishermen that lost 590 vessels, 1,800 fishing gear, and 67 boat engines in Sofala province. In Zambézia province, aquaculture producers lost 169 fish ponds, two cages, and 606,000 lost fry, while in Sofala province, 58 fish tanks, 204 cages, and 257,500 fish fry were lost. Overall, our study reveals the vulnerability of fisheries and aquaculture to extreme events particularly the cyclones in Mozambique. Lack of knowledge regarding climate change, advanced preventive measures, and poor adaptive capacity makes the sectors more vulnerable to disasters. Therefore, it is recommended to improve awareness programs, introduce measures and policies that promote resilience and optimum adaptive efficiency.

Keywords: climate change, climatic events, aquaculture, fisheries, cyclone, Mozambique

INTRODUCTION

The effects of climate change on the ocean environment will continue to impact the fisheries, specially those areas that are suitable for the phenomena to occur (Mendenhall et al., 2020). This impacts brings profound implication to the coastel communities and ecological systems (Palacios-Abrantes et al., 2020; Whitney et al., 2020).

Some recent studies have shown evidence of how the impacts of climate change influence fish stocks and aquaculture production and also the negative effects on coral reefs, causing coral bleaching and altering the species composition and diversity (Munday et al., 2008; Pratchett et al., 2008; Daw et al., 2009; Ateweberhan et al., 2013; Belhabib et al., 2018; FAO, 2020). In this context, it is necessary to understand the impacts of extreme events such as increased temperature, sea-level rise, floods, droughts, and cyclones to predict and understand the dynamics of fish stocks and their impact on future food production systems, as the effects of these events are already being observed in the ocean and coastal areas, impacting the reduction of fisheries stocks (O'Reilly et al., 2003; Vollmer et al., 2005; Badjeck et al., 2010; Rezaee et al., 2016; Blanchard et al., 2017; Troell et al., 2017).

According to FAO (2020), the impacts of climate change tend to be greater in tropical regions of Africa and Asia, where temperatures are higher, contributing to the reduction of fishery productivity. Therefore, creating occupational alternatives to reduce fishing pressure, and increasing the adaptive capacity of fishermen based on the construction of resilient infrastructures in the fisheries and aquaculture sectors are urgently needed to minimize impacts.

The Mozambican coast is very rich in diversity of fisheries species, both for the composition of the different ecosystems that they host, as well as for the environmental characteristics (Hoguane et al., 2012). Fishermen and coastal communities in Mozambique depend mostly on fishery resources that are heavily influenced by climate dynamics (Allison et al., 2005; Badjeck et al., 2010). However, in the last three decades, production has been falling, not only due to the over-exploitation of the resources but also due to climate change (Blythe et al., 2014; FAO, 2020).

However, in recent years Mozambique has suffered cyclical natural events such as cyclones, floods, and droughts, with the central and northern zones being the most affected (Hussein et al., 2020; Malauene et al., 2021). These events directly or indirectly affect fisheries production, catches, and aquaculture production. Although coastal aquaculture is more vulnerable to climate change (Ahmed and Diana, 2015), the impacts of climate change are predicted in the future on continental aquaculture. Since the 2000s, the country has been the center of major climatic disasters in Southeast Africa, being (floods, droughts, cyclones) associated with climate change (INGC, 2009; Arndt et al., 2010; Naess et al., 2015; Samoilys et al., 2019).

In March 2019, the country recorded two major cyclones (Idai and Kenneth) that severely plagued the central region in the provinces of Sofala and Zambézia and part of the northern region in the provinces of Nampula and Cabo Delgado and about 600 people in total died, thousands were left homeless and several infrastructures were totally and or partially destroyed. This was the first time that two events of high magnitude had reached the country simultaneously in the same period leading to many lives being lost and many infrastructures destroyed [Instituto Nacional De Gestão De Calamidades (INGC), 2019; Hierink et al., 2020; Matos and Ndapassoa, 2020].

Studies addressing issues related to climatic events in Mozambique, such as cyclones and floods, mostly focus on health and nutrition, housing, and socioeconomic issues (Asante et al., 2009; Matos and Ndapassoa, 2020). Few studies bring the link between climate change in fisheries and aquaculture in Mozambique, except studies by Gammelsrød (1992) which shows the influence of environmental factors (rainfall) on the availability of shrimp fisheries at Sofala Bank, and by Hoguane et al. (2012) that relate rainfall to artisanal fishing on the tropical coast of northern Mozambique. Other studies highlights the consequences of climate change on both fisheries and aquaculture, creating problems for the sustainability of coastal communities (Blythe et al., 2014; Mucova et al., 2021), while other researchers point out that the quality of life of this communities reduces due to the negative impacts that climate change has on natural resources (Bunce et al., 2010; Techera, 2018). Hence, this study aimed to bring an understanding and characterization of the impacts caused by cyclones Idai and Kenneth on fisheries and aquaculture in the central provinces of Sofala and Zambézia in Mozambique. This brings an overview of the global impacts of the climate change in Mozambique channel and its influence on the artisanal fisheries and coastal community livelihoods. An appropriate understanding of the impacts of climate change is key to the development of appropriate measures for adopting and mitigating the impacts at both producer and policy formulation levels. Besides, the study will also fill the gaps in existing literature on the impacts of climate changing on the fisheries and Aquaculture by understanding the direct and indirect impacts of these two climatic events and also bring out aspects of resilience of fishing communities and aquaculture producers, vulnerabilities of coastal regions as well as the measures that must be taken to safeguard economic, environmental sustainability, and food security.

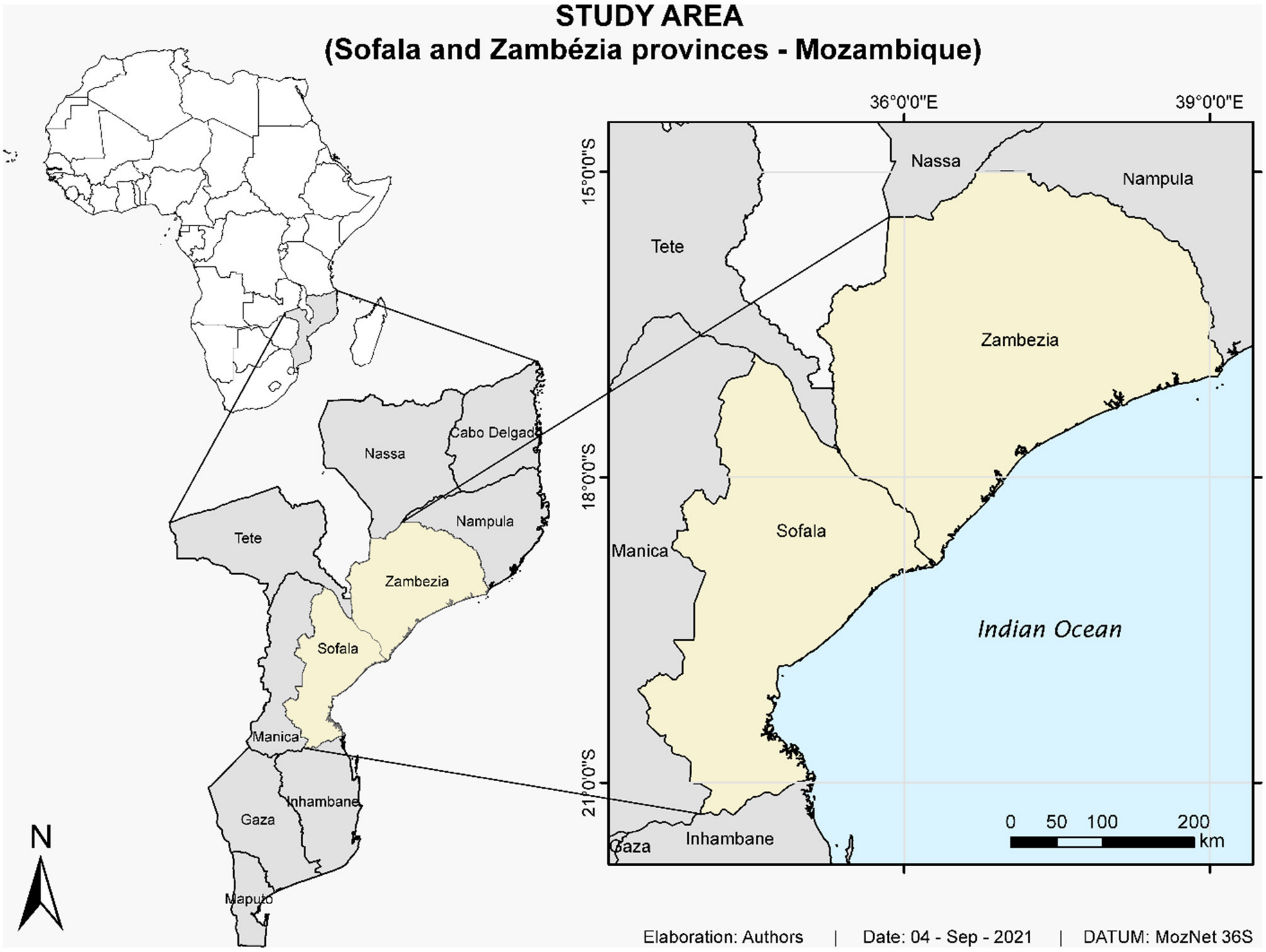

FIGURE 1 | Map showing the Province of Sofala and Zambezia and all the locations of the districts covered in the study. Source: Authors.

MATERIALS AND METHODS

Study Area

The data for this study were collected in March and April 2019 after cyclones Idai and Kenneth in the provinces of Sofala and Zambézia, both in the central zone of Mozambique (**Figure 1**). Mozambique is located in the southeast of the African continent. The country is ranked third among the most vulnerable nation from natural disasters, after Bangladesh and Ethiopia (Wheeler et al., 2007; Artur and Hilhorst, 2012). The study area comprises the two high vulnerable provinces of Mozambique, the province of Sofala and Zambezia. They are characterized by having a high level of exposure of costal climate hazard and cyclones (Niquisse et al., 2017). Although of high extension of vulnerability zone, the marine ecoregion and constaline of this two areas represents the main part of Sofala Bank (the largest fishing ground in Eastern Africa) (Charrua et al., 2020). In the last 20 years, among the biggest natural disasters (Floods, Droughts, Storms and Cyclones), Floods were the most frequent with more than 25 occurrences (49%) followed by severe storms, 15 occurrences (29%), period over 17 tropical cyclones occurred in Mozambique, with cyclone Idai and Kenneth being the most significant (EM-DAT, CRED/UCLouvain, 2020; Hierink et al., 2020). In 2000, the country experienced one of the greatest floods, in which it left more than 800 deaths, thousands of people displaced and several housing infrastructures destroyed (Artur and Hilhorst, 2012; EM-DAT, CRED/UCLouvain, 2020). Data published on disasters in Mozambique show that there is an increase in the frequency of occurrence and intensity of natural events such as cyclones, floods, and droughts in the country (Christie and Hanlon, 2001; Negrão, 2001; INGC and FEWS, 2003; Artur, 2013). Although natural disasters are cyclical in Mozambique, the construction of fisheries and aquaculture infrastructure still dominates in regions very close to the coast, creating conditions for vulnerability to disasters.

Study Design and Data Collection

The collected data was on impacts caused by cyclones Idai and Kenneth in the provinces of Sofala and Zambézia (**Figure 1**). Primary and secondary data were used, where the primary data consisted of field reports generated by the department of fisheries and aquaculture after the events, and the secondary data were collected from qualified literature and information from different actors through non-structured interviewers (fishermen, fish farm managers) aquaculture production, and fisheries companies in the respective affected provinces. These group of information where taken separately and with specific question according to their action area (fishermen and aquacultures producers). The data was divided into three areas: Fisheries, Aquaculture, and vulnerability maps. In fisheries, the main issues that were addressed are related to direct impacts (loss or damage of vessels and engines, fishing gear, amount of fish lost) while for aquaculture, the direct impacts were: number of producers affected, production infrastructure (tanks, cages, and hatcheries) destroyed, lost fry, production area affected and lost production, while the indirect ones were difficulties in transporting inputs for aquaculture production and, damage of support infrastructures. Additionally, we used some fisheries report from the minister of Sea, Inland Waters and Fisheries in order to collect data of fisheries and aquaculture from previous years. Finally some relevant information was observed by the authors during field visits that consisted on the conversation with fishermen in some fishing centers regarding their vison of fisheries after the event and their challenges.

Data Analysis

The research data were characterized into quantitative and qualitative for analysis. In order to evaluate the impacts of the cyclone on the production and infrastructure of the fisheries and aquaculture, the data were grouped in Excel spreadsheets for the production of graphs and tables and Minitab version 16 statistical package was used for descriptive analysis, for later interpretation.

To understand the distribution of spatial patterns and affected areas, the data already included in excell, were imported into ArcGis to make the representation of data (losses of fingerlings, affected areas and destroyed tanks), so that it would provide a base of information to the government for possible prioritization of interventions in the recovery process. The equal class classification algorithm was also used to produce the thematic map, where the intervals were divided into equal sizes in order to emphasize the quantity of an attribute value in relation to the other values.

ArcGis was also used to prepare a global map of cyclone trajectories, a map of districts vulnerable to flooding and a hypsometric map. For the first two qualitative data referring to the shapefile format obtained from The Humanitarian Data Exchange portal were used, being represented in the form of a map. For the preparation of the hypsometric map, points quoted

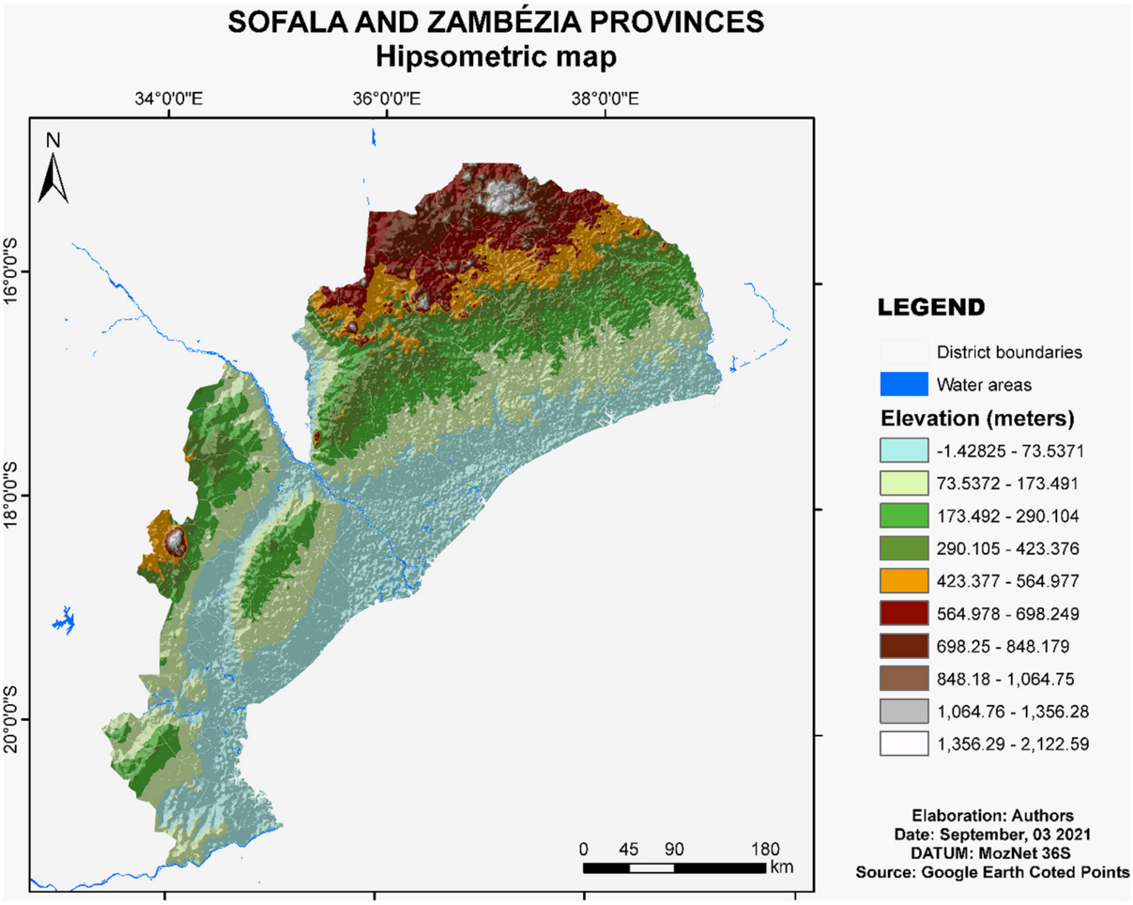

FIGURE 2 | Hypsometric map. Source: Authors.

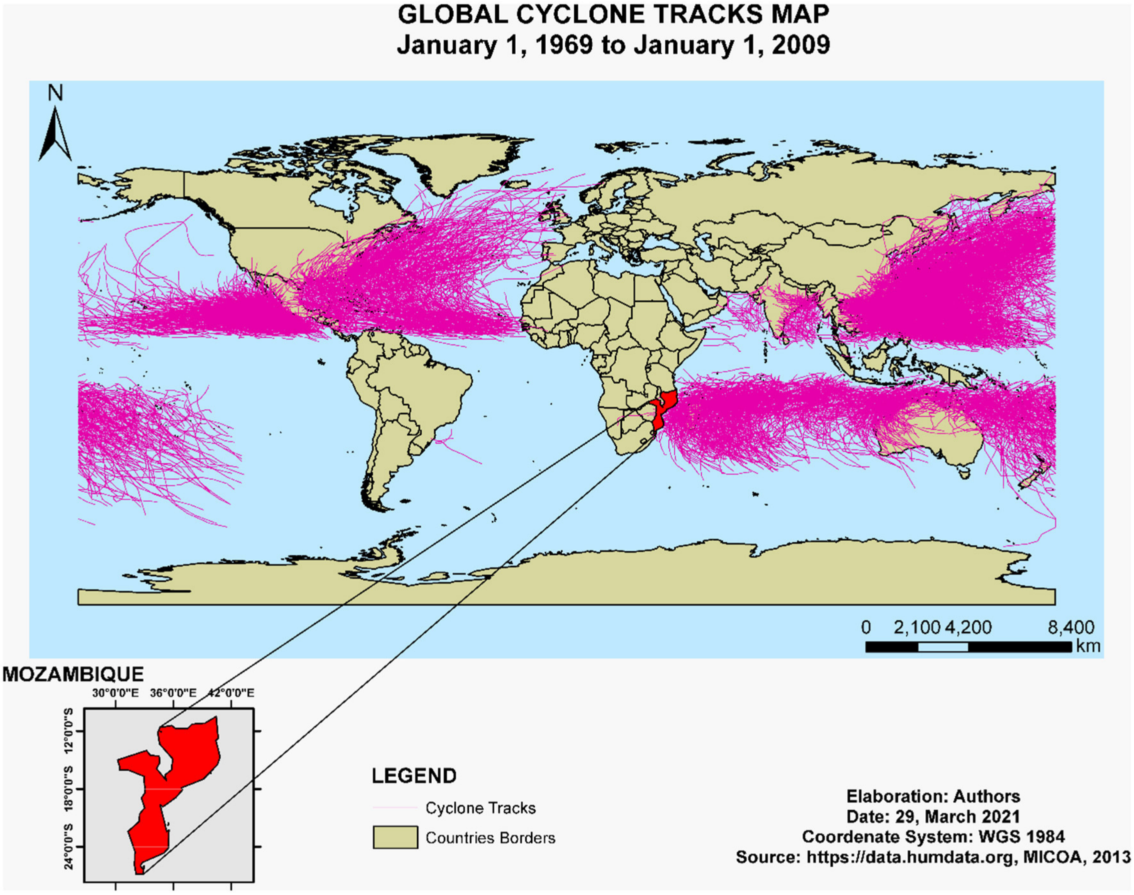

FIGURE 3 | Global cyclone tracks map. Source: Authors.

in google Earth were collected, which, after saved in KML format, were converted to GPX through the Online GPS Visualizer application and later converted in ArcGis to feature format and finally the Digital Elevation Model (MDE) was created.

RESULTS

Fishermen's Experiences Concerning Climate Change

The topographical location of Sofala and Zambezia are shown in **Figure 2**. Based on these locations, it appears that they are located in the coastal zone and predominantly of low altitude, with an extensive drainage network where three main rivers stand out, the Zambezi River and the Púnguè and Licungo River. Due to this characteristic of these regions, the occurrence of cyclones is usually accompanied by strong winds, tropical storms and rains followed by floods.

Conversations and information were collected in the post-cyclone field. Although many of the results presented here are directly linked to the impacts of cyclones, there is also information on what fishermen have observed over the years concerning, for example, the scarcity of fishing resources. During the conversations with fishermen, it was possible to observe that although they did not perceive the impacts of phenomena such as sea temperature rise, sea-level rise, changes in rainfall patterns, and changes in the salinity of the surface of the ocean, they were aware of the reduction in fisheries production over the years, alteration of places with fish abundance, disappearance or reduction of certain fish species and vulnerability of their regions.

TABLE 1 | Previous production (in tons) statistics in the two provinces in Mozambique affected by the cyclones (MIMAIP, 2020).

Province	Production	2017	2018	2019	
				Actual	Expected
Sofala	Fisheries (tons)	46.422	57.463	51.292	60.154
	Aquaculture (tons)	73.4	180	147	1,611
Zambezia	Fisheries (tons)	64.914	76.949	87.169	79.887
	Aquaculture (tons)	128.45	211	360	388

Vulnerability of Coastal Areas to Natural Disasters in Mozambique

Through the map (**Figure 3**), it can be seen that the trajectories of cyclones tend to form agglomerations, showing that these events have a defined spatial distribution and the Mozambique

TABLE 2a | Summary of impacts of cyclone Idai and Kenneth on the aquaculture sector in Sofala Province (a) and Zambézia (b).

Districts	No. of affected producers	Affected ponds	Affected cages**	Fry lost	Affected area		Production lost (Ton)
					Ponds (m²)	Cages (m^3)	
Gorongosa	108	50	-	25,000	5,000	-	7,5
Muanza	24	2	-	5,000	1,000	-	1,5
Beira	2	1	50	141,000	1,800	340	42,3
Búzi	50	2	20	31,000	1,000	136	9,3
Dondo	116	-	56	-	-	380.8	-
Nhamatanda	4	3	40	47,500	600	272	14,25
Machanga	10	1	3	8,000	500	81.6	2,4
Total	314	59	169	257,500	9,900	1,210.40	77,25

**Cages were measured in cm^3.*

TABLE 2b |

Districts	Affected areas (m^2, ha)	Destroyed ponds	Fry lost
Dere	960	4	6,000
Gilé	7,200	24	36,000
Gurue	3,000	10	15,000
Ile	6,300	21	31,500
Inhassumge	3,825	7	10,500
Lugela	5,700	19	28,500
Maganja da Costa	900	3	4,500
Mocuba	7.6*	2 (Cages)	6,000
Morrumbala	900	3	4,500
Namacurra	8,100	8	32,000
Namaroi	3,300	11	16,500
Nicoadala	6,500	13	42,250
Nicoadala (Muziva)	13,900	33	350,000
Quelimane	4,550	13	22,750
Total	65,135**	171	606,000

**Total only for Ponds, *Cages were measured in cm^3.*

channel is covered by these agglomerations. This factor increases the risk for cyclone events that are generally characterized by strong winds and floods in this region. Among them, it is worth mentioning the cyclones Idai of category 2 in March 2019 and Kenneth of category 4 in April of the same year. The two cyclones caused widespread destruction, damage, and loss of human life besides affecting the fishing and aquaculture activities through destruction of infrastructures for production and the loss of fish and fish fry.

Fisheries and Aquaculture Production Statistics Before the Cyclones

The previous fish production statistics in tons by both fisheries and aquaculture in the two affected provinces of Mozambique as reported by the MIMAIP (2019) are shown in **Table 1**. As indicated, there was a steady increase in the production by fisheries and aquaculture in both Sofala and Zambezia provinces from 2017 to 2018. However, in 2019, the production by both fisheries and aquaculture decreased in both provinces, while an increase was observed in Zambezia for both production types. Furthermore, except for fisheries production in Zambezia, all the production quantities recorded in 2019 were less than what was projected. Surprisingly, the fisheries production in 2019 for Zambezia was more than the projected quantity.

Impacts on Aquaculture and Fisheries

In all the sampled areas, it was possible to verify that the indirect impacts were the most observed. In Sofala, where cyclones were more intense, 314 (34%) of producers were affected and the destruction of various production infrastructures including fry production facilities, in addition to 59 (12%) ponds and 169 (44%) floating cages (**Table 2a**). On the other hand, 74% of production was compromised due to the loss of more than 257,500 fry. The province of Zambézia, on the other hand, although it was not the epicenter of the cyclone, had a greater number of affected districts and, consequently, a greater affected area (**Figure 4**). The data show that 169 production ponds were partially or completely destroyed and 606,000 fry were lost (**Table 2b**).

DISCUSSION

Tropical cyclones are considered the most devastating of all-natural disasters given the level of destruction they cause to regions where they occur. In the case of the Mozambique channel, an anomalous eastern circulation associated with the Pacific La Ninã and hot SST in the southwest Indian Ocean were indicated as mechanisms that support repeated cyclogenesis of tropical cyclones (Chikoore et al., 2015). Thus, the vulnerability of coastal regions to floods (**Figure 5**) and storms is expected to increase with the future rise in sea level and the level of development along the coast, although this vulnerability also depends on the future characteristics of the storm (Knutson et al., 2010).

On the other hand, based on the topographic profile of the two provinces (**Figure 2**), it appears that they are located in the coastal zone and predominantly of low altitude, with an

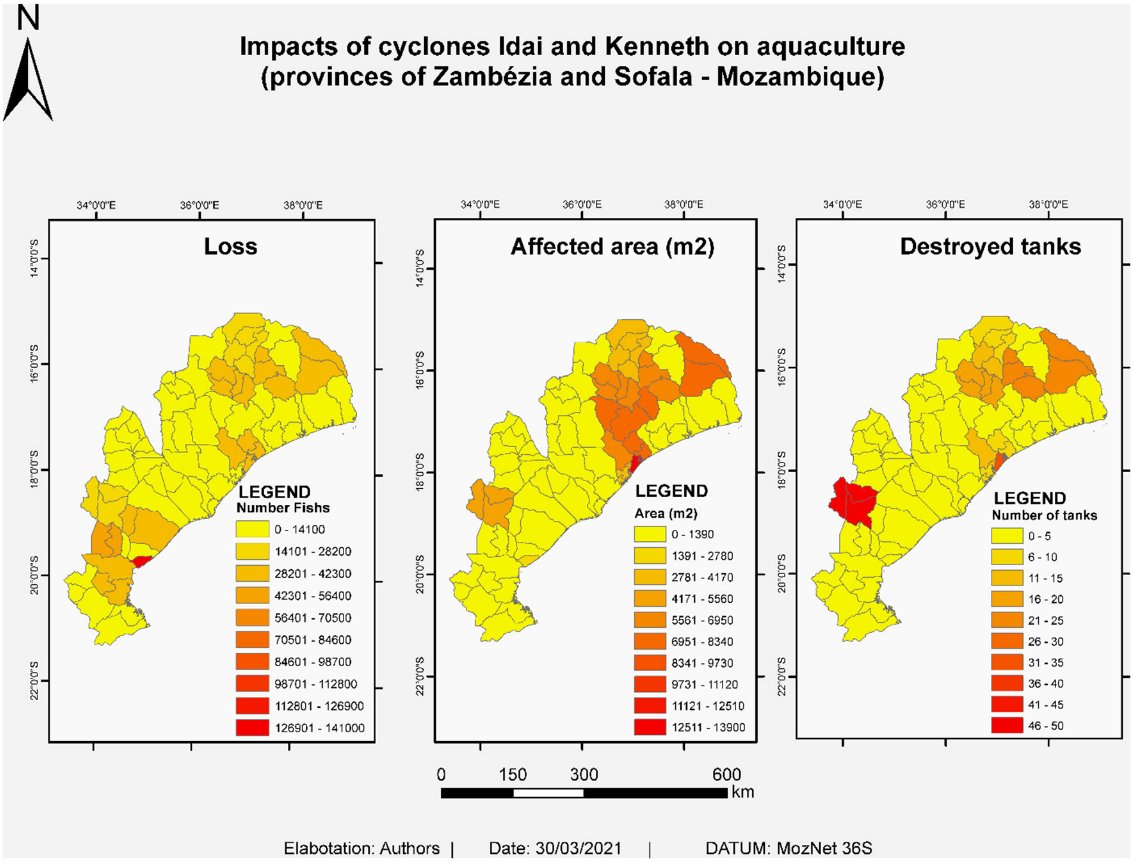

FIGURE 4 | Location of the impacted areas of the cyclones Idai and Kenneth in fisheries and aquaculture. Source: Author.

extensive drainage network where three main rivers stand out, the Zambezi River and the Púnguè and Licungo River. Due to this characteristic of these regions, the occurrence of cyclones is usually accompanied by strong winds, tropical storms and rains followed by floods.

It is therefore clear that the occurrence of cyclones is usually accompanied by flood events which leads to increasing the level of vulnerability and making the level of destruction to aquaculture infrastructure and loss of breeders and fry even greater. This vulnerability is expected to be further exacerbated by the effects of climate change, which are expected to cause the average sea level to rise to almost 1.0 m in 2100 due to global warming at 1.5°C, effects of tides, and tropical cyclones (Mavume et al., 2009; Aparecida de Araújo et al., 2020; Maulu et al., 2021).

Several impacts are associated with the occurrence of cyclones accompanied by floods which affect aquaculture and fisheries systems. Some of these include changes in aquaculture zoning, competition for space with coastal ecosystems providing defense services (i.e., mangroves), reduced freshwater availability, loss of areas such as mangroves and grassbeds that can protect coastal areas from waves, rising sea levels (Handisyde et al., 2014; Riddell and Rosendo, 2015). These impacts include increased infestation of fouling, organisms, pests, aquatic diseases, and changes in production levels (Handisyde et al., 2014; Maulu et al., 2021).

Generally, the impacts of climate change on fisheries and aquaculture are classified as direct and indirect impacts (Handisyde et al., 2006; De Silva and Soto, 2009; Maulu et al., 2021). Direct impacts are linked to the influence of physical and physiological factors that alter the fish stocks in a given production system, in the production of feed, and catches, as well as, influencing changes in species range and genetic variability. While indirect impacts affect the primary and secondary roads linked basically to the structure of production, prices of fishing inputs, production infrastructures, and all the services necessary for production to occur (De Silva and Soto, 2009; Knutsen et al., 2013; Freeman, 2017; Adhikari et al., 2018). The consequences of the climate Change is not restricted to fisheries and aquaculture. This events also causes effects on the coastal agriculture, maritime transportation and harbor damaging, as this area has been flooded and the adjacent area destroyed (Macassa et al., 2021; Montfort et al., 2021). Despite an overall increase in fish production even after the cyclones occurred, it was clear that the expected quantities based on several likely factors, such as the increase in the number producers as is often the case due to population increase. Therefore, climate change may not only decline the production in the fisheries and aquaculture sector but also decline the expected production.

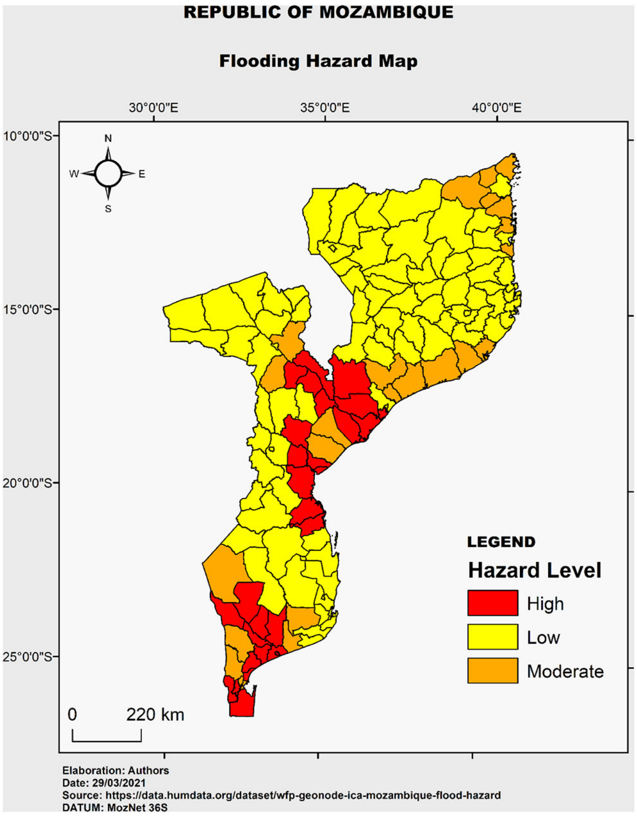

FIGURE 5 | Flooding hazard map. Source: Author.

TABLE 3 | Summary of the impacts of cyclones Idai and Kenneth in the province of Sofala.

Districts	Number of affected fishermen's	Boats affected	Fishing gear destroyed	Destroyed (Motors)	Fisheries lost (Ton)
Beira	372	362	-	37	789
Búzi	338	335	-	17	556
Dondo	350	328	-	-	478
Machanga	250	250	237	5	738
Cheringoma	240	240	-	-	189
Marromeu	202	197	-	-	356
Muanza	325	325	-	8	2,104
Total	2,007	2,037	237	67	5,210

In all the aspects analyzed, the province of Zambezia appeared to have had the greatest impact from cyclone due not only to the greater number of districts with aquaculture production initiatives but also with a greater number of production areas, that mainly small-scale for the livelihood of communities (Villasante et al., 2015; IDEPA Institute of Fisheries and Aquaculture Development, 2020; Muhala et al., 2021). Extreme climatic events such as cyclones, drought, and floods have increased dramatically in recent decades in Mozambique (EM-DAT, CRED/UCLouvain, 2020). Generally, these events have been accompanied by strong winds and heavy rains that lead to the destruction of aquaculture infrastructures. According to De Silva and Soto (2009), extreme events will continue to affect the tropical regions of the world, and coastal aquaculture will be most impacted. On the other hand, Rutkayova et al. (2017) and Maulu et al. (2020), claim that extreme events such as cyclones, floods, and storms, will negatively affect aquaculture production through loss of fish during the invasion of floodwaters in ponds, in addition to the introduction of new species that can create aquaculture unsustainability problems due to the entry of exotic species (Edwards, 2015). In addition, most production tanks in Mozambique are shallow and smaller in size, ranging from 150 to 300 m^2 on average (Companhia and Thorarensen, 2012; Muhala et al., 2021). This factor increases the vulnerability of the ponds to flooding mainly in the lower regions and the invasion of unwanted species [Intergovernmental Panel and Climate Change (IPCC), 2007; De Silva and Soto, 2009]. Some regions of Sofala and Zambezia were characterized by low-lying areas mainly due to the influence of several rivers such as Búzi, Púnguè, Zambezi, and Licungo, contributing to flooding in the surrounding areas during periods of extreme rain.

Most cage aquaculture production in tropical regions of Africa is carried out in lakes, reservoirs, and riverbeds (De Silva and Soto, 2009; Hasimuna et al., 2019; MIMAIP, 2019; Muhala et al., 2021). Cage production in Mozambique is an unremarkable activity. Although emerging, it does not escape the impacts of environmental changes, especially when there are extreme events such as storms and cyclones. In this study, 171 floating cages were affected by cyclones Idai and Kenneth in both provinces. Several studies show that cage aquaculture is the one that suffers the most mainly from mariculture, practiced in the open sea due to its vulnerability (De Silva and Soto, 2009; Maulu et al., 2021), contrary to what was observed in the present study. Edwards (2015), reported that aquaculture in cages on land also suffers the impacts of winds and cyclones, especially if the infrastructure is fragile.

Food security and sustainability from the ocean is a global challenge. Fisheries have been severely impacted by climate change (UN General Assembly, 2014). The central region of Mozambique comprises the most productive coastal oceanic area and covers the Sofala Bank which is the most productive fishing zone in the country where most communities depend on fishing for their livelihood (Hoguane et al., 2012; Darkey and Turatsinze, 2014). Artisanal fishing makes a significant contribution to the economic sustainability of local communities, reaching 70,000–100,000 fishermen and collectors who operate in coastal regions using small motorboats, wooden canoes, and a variety of fishing gear considered as trawls from the bottom, beach trawl, gillnets, handlines, traps and spears (Hoguane et al., 2002, 2012).

According to field observations and informants' testimonies, the effects of climate change were both direct and indirect. Indirect impacts, fishermen claim that they have noticed a decrease in catches and that variations in periods of rainfall and temperatures have influenced not only the type of resources available but also the quantity caught. Our findings were in agreement with the report of Barange et al. (2018) who also noted that extreme events affectes not only infrastructure in the fisheries sector but also production quantities. Therefore, the impacts on the fisheries sector are not limited only to fishermen, but also to the sustainability and food security of the communities that depend on it (Blythe et al., 2014). The vulnerability of coastal communities in Mozambique is notable when a climatic event such as tropical storms and cyclones occur in the region. Mills et al. (2011) demonstrated that although there were other difficulties in the communities of Nigeria and Mali, they still suffered great vulnerability when it comes to fisheries. On the other hand, in some regions of the Sofala Bank, fishermen reported the scarcity of some species that were once abundant. These findings are not restricted to the Sofala bank alone (Barange and Perry, 2009; Brander, 2010; Lam et al., 2020). Regarding the impacts caused by the cyclones, our results revealed that besides the physiological and behavioral aspects described above, the fishing sector suffered high impacts and losses, having affected 2,700 fishermen including the destruction of 2,037 fishing vessels and 237 fishing gear (**Table 3**). Most of the affected fishermen belonged to the artisanal fisheries sector that makes up the majority of fishermen in Sofala Province. The fishing structure in Sofala is artisanal and consists of men and in some cases women who use surface trawls and catch crabs for subsistence (Darkey and Turatsinze, 2014). Motorboats and fishing canoes are the fishing vessel that was commonly used in Mozambique, particularly in the Sofala Bank region for capturing fishery resources (Mualeque and Santos, 2011; Blythe et al., 2014).

Furthermore, due to the precariousness of the materials used during manufacturing, these fishing vessels are destroyed when there are strong climatic events such as cyclones and storms allied to the drainage area that is not safe and without protection. The lack of timely communication of the occurrences of climatic events also leads to poor awareness and consequently negatively impacts fishing communities. Fishermen reported that during the cyclone, many vessels were moored on the edges of the beaches and some within the coastal part of the sea. These factors may have created conditions for them to suffer greater damage when the storms pass. According to Ramenzoni et al. (2020), the impacts of climatic events in the fisheries sector are varied, including changes in ecological conditions, acceleration of coastal zone degradation through soil entrainment, vegetation degradation. Our results agree with those reported by McConney et al. (2009), who identified the effects of climate change on small-scale fisheries in the eastern Caribbean where they indicated a negative biological response from fish when ocean temperatures changed due to climate change.

Challenges and Responses

Climate change and its effects pose challenges to everyone, especially developing countries where predictions of the occurrence of extreme events as a result of climate change have been made, and also the conditions for building resilient infrastructure are weak. Aquaculture production in Mozambique is mostly practiced by small producers and with low investment, needing a lot of help from the government and private sectors to implement it (Muhala et al., 2021). The same small investment scenario can be seen in the artisanal fisheries sector. The biggest challenges that are encountered include a lack of investments for the small-scale fisheries and aquaculture players, to enable them to acquire infrastructure and equipment that can withstand extreme events. On the other hand, poverty and lack of education in most of the actors contribute to the non-adaptation to the stresses caused by climatic events such as cyclones, floods, and storms (Blythe et al., 2014). The lack of education and other income-generating activities exacerbates the fishermen's dependence on fishing activities thereby creating additional pressure on the sector and declining fisheries.

On the other hand, the lack of adequate technical knowledge not only from fisheries and aquaculture actors but also from government and private sectors to create more appropriate measures to adapt to long-term climate change constitute an obstacle for small-scale artisanal fishing and aquaculture. Lack of knowledge for adaptation and monitoring have been reported as major constraints to reducing the impact of climate change on fisheries and aquaculture in Africa, mainly due to a lack of research and institutional development (Lam et al., 2012; Belhabib et al., 2016; Maulu et al., 2019; Samoilys et al., 2019). However, this is also likely to be worsened by the effects of extreme events through destruction on institutional capacity such as research and extension facilities.

CONCLUSIONS AND RECOMMENDATIONS

Climate change is expected to continue impacting Fisheries and Aquaculture as well as on those who depend on these sectors for their livelihoods. While there are efforts to map and show the diverse biological, ecological, and biophysical factors that climate change causes, there is a lack of a clear map to proceed with mediation and prevention when it comes to fisheries and aquaculture in Mozambique. Our study has revealed that the cyclones Idai and Kenneth affected part of aquaculture and fisheries production, leaving various infrastructures and equipment destroyed. Based on the findings of this study and the region's susceptibility, it can be concluded that the negative effects of cyclones will continue to occur and that the first issue that should be prioritized is promoting the adaptive capacity of communities that depend more on the fisheries sector for their survival. Therefore, there is a need to incorporate public policies for the comprehensive dissemination of timely information on the occurrence of climatic events to fishing and aquaculture communities so that preventive measures can be taken well in advance. Lastly, this study recommends that players in fisheries and aquaculture should build more resilient production systems to climate change, such as fish ponds, boats, and canoes.

DATA AVAILABILITY STATEMENT

The data analyzed in this study is subject to the following licenses/restrictions: The data can be found in the Ministry of Fisheries of Mozambique. Requests to access these datasets should be directed to Ministry of Fisheries, Mozambique http://www.mimaip.gov.mz.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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Understanding the Drivers of Production in South African Farming Systems: A Case Study of the Vhembe District, Limpopo South Africa

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Farming systems in South Africa operate against the backdrop of constantly changing environmental, political, and socio-economic conditions. Farming systems are commonly defined by the Food and Agriculture Organization (FAO) as a population of individual farm systems that have broadly similar resource bases, enterprise patterns, household livelihoods and constraints, and for which similar development strategies and interventions would be appropriate. Historically farming systems in South Africa have been characterised by dualism in which large-scale commercial farmers co-exist with small-scale farmers. Although the two farming systems are impacted by the same drivers of production (land, labour, capital, and enterprise), however, they respond to these drivers differently and the nature of the responses reveal their connectivity and possible approaches to sustaining them. A systems thinking approach is best suited to draw possible scenarios of how farming systems in the Vhembe district located in the Limpopo Province of South Africa will respond to changes with respect to the four drivers. In this area, large-scale commercial farming forms a significant component of the production of a number of subtropical crops that contribute to the country's agricultural economy particularly through exports. Simultaneously 90% of rural communities in the district depend mainly on small-scale agriculture to sustain their livelihoods and generate income. The paper provides an overview of the drivers of production for the two farming systems in the Vhembe district and explores how the government can successfully promote development through agriculture by building capacity for the joint success of the two farming systems.

Keywords: farming systems, agriculture, agricultural production, food security, systems thinking

INTRODUCTION

Large-scale commercial farming alongside smallholder farming is a dichotomy that characterises South African farming systems and is a legacy of the Apartheid system. The two farming systems can be compared using a framework for production of which there are four drivers namely land, labour, capital, and enterprise (Dariusz, 2015). There has been some valuable research conducted on farming systems in the Vhembe district over the past 20 years as agriculture contributes significantly to the economy of the Limpopo Province and the country as well as to the provincial food security. Studies have shown that there is a production gap between commercial and small-scale producers in South Africa (Altman et al., 2010; Labadarios et al., 2011; Hendriks, 2014). Commercial agricultural production has been the primary driver of national food security predating democracy in 1994 (Hendriks, 2014). Baiphethi and Jacobs (2009) argue that even though small-scale production is important for household food security, the productivity of the sub-sector in South Africa is quite low. The South African government therefore places particular importance on small-scale agriculture in its efforts to fight food insecurity and poverty. According to Hendriks (2014), while the focus of agricultural production and marketing programmes in South Africa has shifted to small-scale production, legislative, and policy measures for creating an enabling environment for smallholders to establish sustainable and competitive production and marketing systems have not been provided. Hendriks (2014) further suggests that many of the elements that helped establish commercial farmers and ensure national food security such as input subsidies, infrastructure, security of tenure, market protection, credit etc. are either no longer available or non-functioning to both commercial and small-scale sectors. More recently Nwafor and van der Westhuizen (2020) proposed that smallholder farmers could improve their competitiveness through participating profitably and sustainably in agricultural supply chains. This has become the focus of a growing body of research (Giller et al., 2021; Marinus et al., 2022).

Statistics South Africa (StatsSA) (2017) revealed that the Limpopo Province has the highest number of households involved in agriculture in the country with 41% involved in agricultural production of some kind (De Cock et al., 2013). Despite this statistic the same source highlights that 91.5% of these households practise farming at a subsistence level as an additional food source and only 4.4% is engaged in agriculture as an additional source of income. Olofsson (2018) draws our attention to the fact that up to 41% of small-scale tree crop farmers in the Vhembe district depend primarily on welfare in the form of state pensions, available from the age of 60 years onwards, as their main livelihood source. These were used to purchase food from markets to supplement food obtained from home gardens.

Although the government desires to improve the quality of life of its citizens through farming and building capacity to farm high value crops (HVCs) that can contribute to food accessibility through profits made from sales and participating in export markets, the context of the dualism of the farming systems and their response to the drivers of production presents itself as a complex problem. Numerous debates have emerged within different spheres of government and amongst scholarly researchers surrounding the question of how the co-existence of South Africa's two main farming systems can be sustained. An understanding of the dynamics of how the factors of production affect South African farming systems and as a result contribute toward the transformation of agriculture in the country is paramount. There is need for an adequate evaluation of the farming systems in order to explore how they can continue to co-exist. The objective of the study is to understand the factors of production under the two farming systems in South Africa in order to explore the plausibility of various approaches that can be applied to support the development of these farming systems for purposes of long-term sustainability of agriculture in the country. Though the four drivers of production affect both farming systems significantly and intersect at various levels, for the purpose of this paper's discussion all four drivers are addressed generally however greater emphasis will be on land due to its contentious reputation and its significance in a politically-sensitive part of the country as the one chosen for the study.

CONTEXTUALISING THE DRIVERS OF PRODUCTION IN SOUTH AFRICAN FARMING SYSTEMS

The context of the dichotomous nature of South African farming systems is unique to South Africa and differs vastly from farming systems in other African countries given the historical background of apartheid and its aftermath (Garrity et al., 2012). The dual nature of the farming systems significantly affects productivity across all four drivers of production as can be seen in the following sections.

Land

Land is arguably the most critical driver of production in both large-scale commercial and small-scale farming systems in South Africa. There is a plethora of issues that pertain to land as a driver of production of which land access, availability, tenure, quality, and management of the land can be identified as major issues. Land management differs between the farming systems and becomes a key concern because it will determine the sustainability of the land. Land management is influenced by availability of land and tenure security amongst other factors. With regard to availability of land to the two farming systems, historically small-scale farmers, demographically classified as black, who made up the majority of the population were allocated limited proportions of land in the former homelands areas known as Bantustans (Van den Berg, 2013). This land was mostly of poor quality in comparison to the arable land allocated to their white South African counterparts who formed the minority (McCusker, 2004). This disparity in land availability is seen in the Limpopo province. There was reportedly a total of 5,000 commercial farming units in the Limpopo Province in 2002 (Whitbread et al., 2011). This number steadily decreased to 3054 in 2017 (8% of the national total) (Statistics South Africa (StatsSA), 2017) which corroborates the assertion made by Walker and Dubb (2013) that commercial farming units in South Africa have been rapidly decreasing since the 1990s. Although the exact number of commercial farming units in the Vhembe district is not specified, according to Oni et al. (2012) 174830 ha of arable land (70% of the total for the district) is owned by white commercial farmers while small-scale farmers own 74927 ha (30% of the district total). Olofsson (2018) describes the present state of small-scale farmers in the Vhembe district where farmers continue to be confined to overpopulated areas where land access is severely limited and land is governed by traditional authorities under a communal land tenure system. This communal land tenure system limits the production capacity of small-scale farmers as the combination of a lack of tenure rights and overlapping land uses restricts their ability to sustain production in the long term (Burger, 2021). Large-scale commercial farmers in the Vhembe district typically own the land they farm on (Olofsson, 2021) and this places them at an advantage as they are able to make more long-term production decisions. In terms of land quality as it pertains to fertility, irrigation plays a crucial role for the two farming systems. Irrigation promotes crop production throughout the year and crop diversification because of the availability of water. Irrigation is commonly practised by large-scale commercial farmers in the Vhembe district (Tapela, 2008). Most small-scale farmers in the district on the other hand depend on rainfed agriculture. According to Mpandeli (2014) rainfed crop yields amongst small-scale farmers are generally poor due to low and erratic rainfall coupled with already poor soil fertility.

Labour

Labour is also a key driver of production in South African farming systems. Some of the main issues of concern surrounding labour include the type of labour, i.e., permanent or seasonal, labour availability, quality, and management of labour with respect to decision making. There is heavy reliance family labour amongst small-scale farmers in South Africa and the Vhembe district in the Limpopo province is no exception. Labour is hired seasonally and to a limited extent mostly during the harvest season. Olofsson (2018) mentions the unique situation of smallholder tree crop farmers in the Vhembe district who rely primarily on their own labour, with some additional help coming from seasonal labour and family members and operate at a relatively small scale of production. This is in sharp contrast to their large-scale commercial farmer counterparts who according to Hall et al. (2013) have historically depended on hired seasonal and permanent labour to support large-scale production. The availability of seasonal labour is essential to the management of high value horticultural crops such as those typically found in the Vhembe district. The limited extent of hired family labour can be attributed to the size and demography of rural families which are impacted by urban migration patterns. According to Nhemachena and Hassan (2007) in most rural smallholder communities in Limpopo males are more often based in town as they seek for employment there, leaving much of the agricultural work to women. Mugovhani and Tshishonge (2012) highlight that the frequent absence from home of adult males involved in migrant labour in the Vhembe district resultantly increased social responsibility for women and boys. Hall et al. (2013) indicate that migration ushers in new patterns of displacement that bring migrants and refugees from the neighbouring country of Zimbabwe to Limpopo's farms and this has implications on the source of labour for small-scale farmers. Labour for large-scale commercial farmers on the other hand is generally hinged on costs.

In attempts to maximise profit, large-scale commercial farmers opt for mechanisation as an alternative to hired labour which can potentially reduce labour costs. Hall et al. (2013) suggest that this shift to a less labour-intensive production and increased mechanisation is a major driver of change in commercial agriculture in South Africa that is shaping the lives of workers on farms in the Limpopo Province. An unintended consequence of this shift in reliance on hired labour amongst large-scale farmers is a negative impact on labour relations between farmers and laborer's where members of the local communities feel excluded from participation in farming activities for production. The issue of what will promote the sustainability of production in terms of labour for South African farming systems remains unresolved.

There is ongoing research into what approach will result in success whether mechanisation is the best solution for both farming systems or a combination of mechanisation and hired labour. Due to the numerous constraints encountered by small-scale farmers across the country it is challenging to determine whether they have the capacity to replace the existing family labour structure with the adoption of new technologies and mechanisation.

Capital

Capital to support farming systems is yet another important driver of agricultural production. If neither of the two farming systems have access to sufficient capital, then the farming systems cannot be sustained. Most large-scale commercial farmers have access to capital from large commercial institutions. Greenberg (2013) points out that production finance in South Africa was historically provided for by state and statutory institutions such as the Land Bank and the Agricultural Credit Board. The Land Bank is said to have continued to play a valuable role in agricultural financing of commercial farmers in the province mostly excluding black producers (Cousins, 2016). Small-scale farmers on the other hand have limited access to capital which directly impacts the scale at which they can operate. Limited access to capital presents itself as a constraint to the farming of HVCs amongst small-scale farmers as the input costs for these crops are high. The lack of tenure rights for small-scale farmers alluded to earlier means farmers are unable to pledge land or income from harvests as surety for loans to improve their land (Burger, 2021). As a result of limited access small-scale farmers have to explore multiple avenues of generating capital such as diversifying farming systems to include livestock (Whitbread et al., 2011). Sale of some of the livestock serves as an alternative capital source. Other sources of capital amongst small-scale farmers include savings, money borrowed from family members and even money inherited from deceased family members. In order for small-scale farmers to transition into farming at a commercial level they need reliable sources of capital.

Enterprise

The issues of enterprise selection and combination are crucial to production in South African farming systems. Selection of the enterprise for small-scale farming systems is not based solely on profit. There are other considerations that must be factored into decision making such as the lack of land tenure security, the quality of the land and access to capital referred to in preceding sections. When small-scale farmers are unable to access capital from large financial institutions, they still need cashflow in order to cover running costs of farm operation and production for profit. It is common to find mixed enterprises amongst small-scale land holdings in South Africa. Small-scale farmers tend to mix the farming enterprise for example incorporating livestock alongside HVC farming. Beside the fact that livestock have social and cultural significance and are often used for cultural ceremonies, livestock can also be sold for additional income to reinvest in agriculture. Home gardens which include vegetables and nuts alongside the farming of HVCs are another example of mixed enterprises. Maize is the predominant cereal grain grown in the district among small-scale farmers (Odhiambo and Mag, 2008). Leguminous crops like groundnuts, bambara nuts and cowpeas are also grown by small-scale farmers as well as vegetable crops which include spinach, cabbage, tomatoes and onions (Obadire, 2010). These are grown for the farmers' own consumption with any surplus sold to neighbours or relatives. Sales from home garden produce are used to support the farming operations and resultantly sustain small-scale farming systems.

Theoretical Framework

South African farming systems operate against the backdrop of constantly changing environmental, political, and socio-economic conditions. It is within this context that agricultural production needs to be understood as it forms and important component of the water, energy, and food security nexus in a changing climate. A systemic approach to addressing agricultural development is necessitated by the reality of heterogenous approaches to production by way of the response to the drivers of production by the two dominant farming systems. Systems analysis is a valuable tool for the evaluation of complex problems such as that presented by the duality of farming systems in South Africa. Arnold and Wade (2015:7) define systems analysis as *"a set of synergistic analytic skills used to improve the capability of identifying and understanding systems, predicting their behaviours and devising modifications to them in order to produce desired effects."* The application of systems analysis is rooted in the theoretical understanding of systems thinking which the same authors define simplistically as *"a system of thinking about systems."* (Arnold and Wade, 2015: 670). Systems thinking is based on the understanding that with globalisation comes increased interconnectedness and interdependence on systems that govern human existence (Meadows, 2008). The overlap in the various components of these global systems presents a complexity that necessitates a diversity of interventions and a systems dynamics (SD) approach to addressing complex problems. Simonovic (2012) describes systems dynamics as the understanding of the relationship between integrated systems elements and how they impact each other's behaviour.

METHODOLOGY

Study Site

The Vhembe district is a district municipality in the Limpopo Province of South Africa that is farthest north (**Figure 1**); sharing a border with Botswana and Zimbabwe in the north-east and Mozambique in the south-east through parts of the Kruger National Park (Maponya, 2021). The district is one of the five district municipalities that constitute the Limpopo Province. Out of an area of 2,140,708 ha, 247,757 ha of the land in the Vhembe district is arable (Setshego et al., 2020). Four local municipalities are found within the Vhembe district: Mutale (renamed Collins Chabane), Thulamela, Makhado and Musina. The South African governance structure regards the composition of local municipalities as towns and their surrounding rural areas (Independent Electoral Commission (IEC) of South Africa, 2016). The main towns within the district are, Malamulele, Thohoyandou, Makhado, and Musina, respectively, for the four local municipalities.

The Soutpansberg mountain range divides the Vhembe district into two agro-ecological systems. The northern side is largely semi-arid, with livestock farming and game ranching being the main activities and some limited horticulture where water is available; this is comprised of the local municipalities of Musina and Mutale. The southern side, comprised of the local municipalities of Thulamela and Makhado, is a subtropical regional hub with high rainfall, in excess of 700 mm per annum, making it suitable for the cultivation of subtropical fruits, cereals, vegetables, and nuts (Oni et al., 2011). The Vhembe district forms a significant component of the production of a number of subtropical crops that contribute to the country's agricultural economy particularly through exports. According to Kom et al. (2020) the well-established white commercial horticulture farming is generally found on the southern side of the district (local municipalities of Makhado and Thulamela). It is mainly made up of stakeholders in the subtropical industry which includes commodities such as litchis, bananas, mangos, avocados, citrus, and pecan nuts. Another subtropical crop found dominantly in the southern side of the Vhembe district is macadamia nuts.

Geographically, the Vhembe district covers a location that is predominantly rural (Rusere et al., 2019), which is characteristic of the Limpopo province. According to DAFF (2013) 89% of the population is classified as rural, therefore agriculture plays a prominent role in the economic development of rural areas in the province. The Vhembe District Municipality (VDM) (2014) reports that 90% of rural communities found in the Vhembe district depend mainly on agriculture to sustain their livelihoods and generate income. Maponya (2021) indicates that agriculture in the Vhembe district is one of the economic drivers that contribute to the Limpopo Province and nation at large. The Vhembe district produces 4.4% of South Africa's total agricultural output, 8.4% of the country's sub-tropical fruits and 6.3% of its citrus according to the Vhembe District Municipality's Local Economic Development Strategy (2020). A large proportion (70%) of the farming activities in the Vhembe district can be accounted for by small-scale agriculture and the remaining 30% is commercial agriculture (Odhiambo and Mag, 2008; Oni et al., 2012; Olofsson, 2018).

In terms of viability for agriculture, the district is located in a semi-arid area, is frequently affected by dry spells that often develop into severe drought and experiences severe water shortages from May to August (Rusere et al., 2019). The same authors document that most commercial farmers in the district

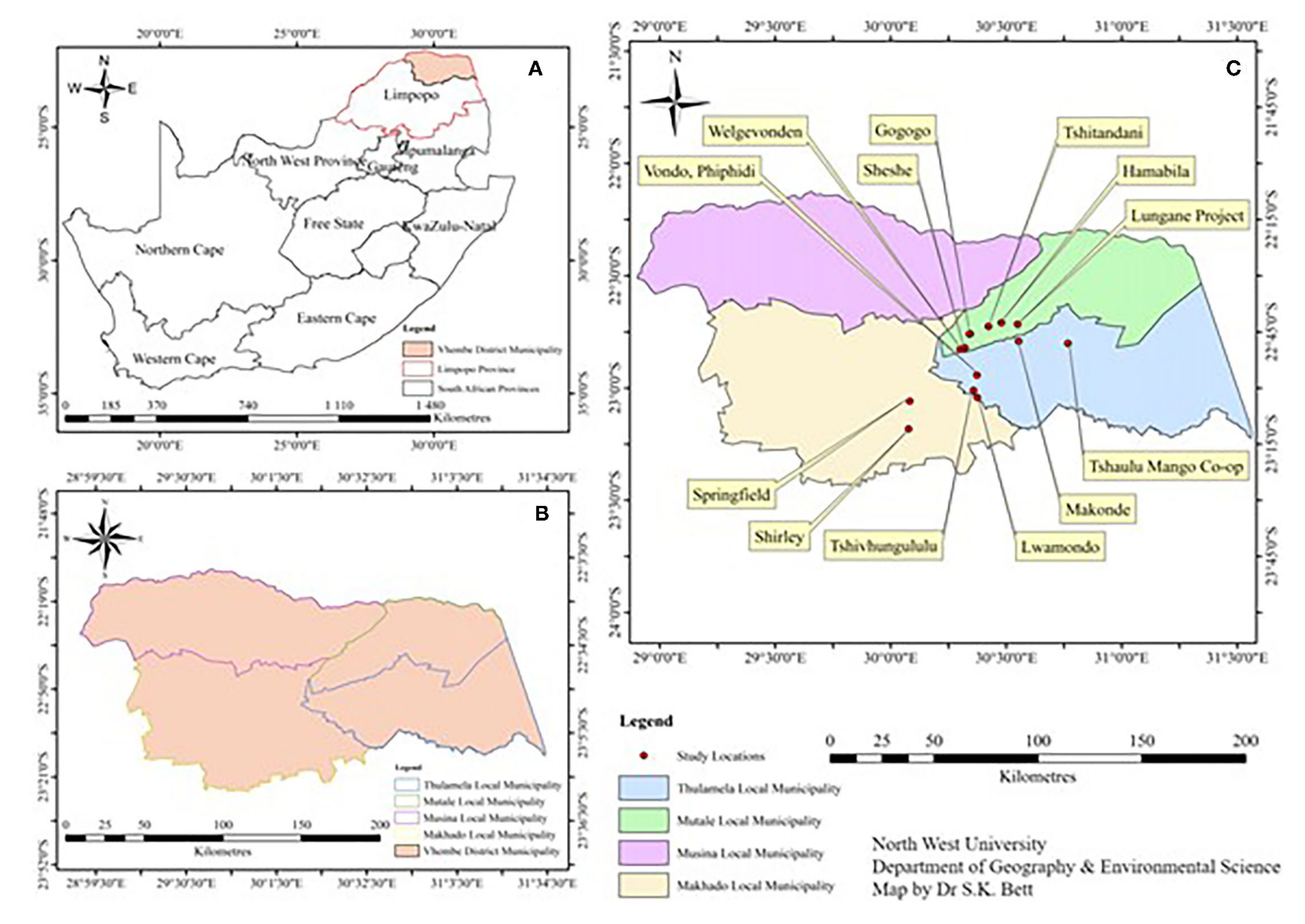

FIGURE 1 | Map showing the location of **(A)** The Republic of South Africa's Provinces and provincial boundaries, highlighting the location of the Limpopo Province and the Vhembe district within the Limpopo Province of South Africa **(B)** shows the location of the four local municipalities within the Vhembe district and **(C)** shows the locations and names of the farm sites within the Vhembe district that were sampled in the study.

depend on irrigation systems for farming whereas the small-scale farmers mostly rely on seasonal rainfall which typically falls from November to March. According to Moeletsi et al. (2013) seasonal rainfall (October-April) in the southern side of the district, identified earlier as including Makhado and Thulamela local municipalities and a horticulture hub, ranges from 400 to 600 mm. The average rainfall for the southern side ranges from 246 to 681 mm per annum (Rusere et al., 2019). Soils in the Vhembe district are variable and tend to have a higher loam and clay content toward the east but are sandy in the west (Odhiambo and Mag, 2008; Rusere et al., 2019). Moeletsi et al. (2013) state that soils in the southern region of the Vhembe district vary significantly from one place to another with most parts having Glenrosa and Hutton soils according to the South African soil classification (SA Soil Classification, 1991).

According to the census of commercial agriculture in 2017, the biggest crop output in the Vhembe district was fruit, mainly subtropical and citrus (Statistics South Africa (StatsSA), 2017). The district ranked third as the largest driver of agricultural production amongst the five districts in the province generating R5.4bn. The census also ranked the Vhembe district as the third biggest agricultural employer in the province employing 17,714 employees in large-scale commercial operations (Statistics South Africa (StatsSA), 2017).

Study Design

The study was conducted by analysing primary and secondary data to identify and characterise small and larger-scale farming systems of three tree crops in the Vhembe district namely macadamia nuts, avocados, and mangos. The aim of the analysis was to highlight the connectivity of interactions within and between the two farming systems in relation to the four drivers of production, i.e., land, labour, capital, and enterprise. Secondary data were collected from numerous sources: peer reviewed research articles, books, the official database of subtropical crops from the local Department of Agriculture, climate data from the Institute of Soil, Climate and Water (ISCW), and data of soils and land type from the Agricultural Research Council (ARC). The target population consisted of a combination of small-scale and large-scale commercial farmers of the three commodities within the district. Farming systems were first broadly categorised based on information extracted from the subtropical crop database which contained data on farm location (detailing the village or town and local municipality), gender of the farmer, farm size (ha) and the farmers personal contact details. A purposive sampling method (Ames et al., 2019) was used to select criteria for site selection. The four chosen criteria were farm size, commodity, farm location, and gender of the farmer. The database contained this information for six subtropical crops namely, litchis (92), avocados (204), bananas (23), macadamia nuts (184), citrus (90), and mangos (528). In total the database documents a total of 1,121 subtropical crop farmers in the Vhembe district. Based on the database information the three commodities selected for the study are the most commonly farmed commodities in the Vhembe district. This influenced the choice of commodities. Furthermore, macadamia nuts were selected based on their known export value as high HVCs and their significance to the country's agricultural economy while avocados were selected based on farmers' expressed willingness to participate in the study derived from preliminary interaction with farmers at a local study group information sharing meeting. Mangos were selected on the basis of having the largest number of documented farms on the database suggesting their popularity as a farming crop. With regard to farm size, farms were chosen using a systemic random sampling procedure to ensure equal representation within the various categories of size that are found in the database, namely small-scale (1–10 ha) and large-scale (11 ha and above) as the study required farmers with both smallholding and larger holdings. For the criterion of location farms were selected that reflected equal representation of all four local municipalities the characterise the Vhembe district namely Thulamela, Musina, Makhado, and Mutale. The last criterion for farm selection was famers' gender. A random number generation method was employed to ensure there was equal representation of both genders across the farms. The process of random number sampling was carried out by allocating a number to the selected farmers using the previously stated criteria, writing down the numbers and placing the m in a container. The researcher than randomly picked out numbers from the container to make up a total of 12 farms. The 12 farms were comprised of four samples for each of the three commodities spread across the four municipalities with two small-scale and 2 large-scale farms and an even combination of male and females. A detailed characterisation of the three farming systems based on the four drivers of production followed after the initial site selection. In-depth, on-site interviews with farmers provided primary data. Snowball sampling (Etikan et al., 2016) was used to conduct the interviews with farmers in selected farm locations with the objective of maintaining the same initially selected sample size. The outcome of the snowball sampling technique produced the following number of samples: mangos (4), macadamia nuts (7), and avocados (8). In total 19 farmers were selected to participate in in-depth interviews based on their availability and willingness to participate. Due to the extremely rural location of farm sites and challenges in accessing farms and farmers, data were collected at only one point in time. This explains the exceptionally small sample size which is acknowledged.

Data Collection

Face-to face interviews with farmers on-site at the farm locations were conducted over two visits to the Vhembe district in October and November 2020. Ethical clearance (number H19/09/26) was obtained from the University of the Witwatersrand ethics committee, as well as from the Local Department of Agriculture by way of an official letter of approval. Due to language barriers the researcher conducted the interviews alongside a local field assistant who served as an interpreter. Interviews were conducted in the local Vhenda language.

In-depth Interviews

The main instrument of data collection was a questionnaire made up of a combination of open and close-ended questions aimed at collecting both quantitative and qualitative data. Close-ended questions were used to obtain statistical information regarding the four drivers of production while open-ended questions were used to enable participants to provide more detailed answers. The questionnaire was divided into four sections: land, labour, capital, and enterprise.

Data Analysis

Qualitative data were analysed using descriptive statistics (Sarka, 2021) by calculating averages, percentages, and standard errors. Student t-tests and Chi squared tests (Shen et al., 2021) were used to compare the means across the two categories of farm size and between the different commodities. Qualitative data were analysed through the use of thematic analysis (Grodal et al., 2021) of participant responses to open-ended questions related to the drivers of production across the different commodities and between the two farm sizes. Responses from these questions were categorised into dominant themes and sub-themes. Emerging themes were triangulated with quantitative data in order to explain phenomenon.

RESULTS AND DISCUSSION

Results have been selected that speak to key issues raised under the sub-theme: Contextualising the drivers of production in South African farming systems. In line with the authors' decision to focus specifically on land as a driver of production, results reflect issues highlighted to this end.

Land Ownership

The predominant land ownership amongst participants in the study was communal (74%) compared to 26% who owned the land that they farmed on. Only a few macadamia (16%) and mango (5%) farmers owned the land compared to avocado farmers (26%). Results of the Chi-Square test revealed that the differences in land ownership between the three commodities are insignificant, $\chi^2(2, N = 19) = 3, 8, p > 0.05$. Results revealed higher proportions of small-scale farmers who farmed on communal land across all three commodities compared to those who owned the land (**Figure 2**). There was an insignificant difference between farm size and land ownership [$\chi^2(2, N = 19) = 0, p > 0.05$] amongst participants. This disparity in ownership reflects the common reality of tenure rights amongst farmers

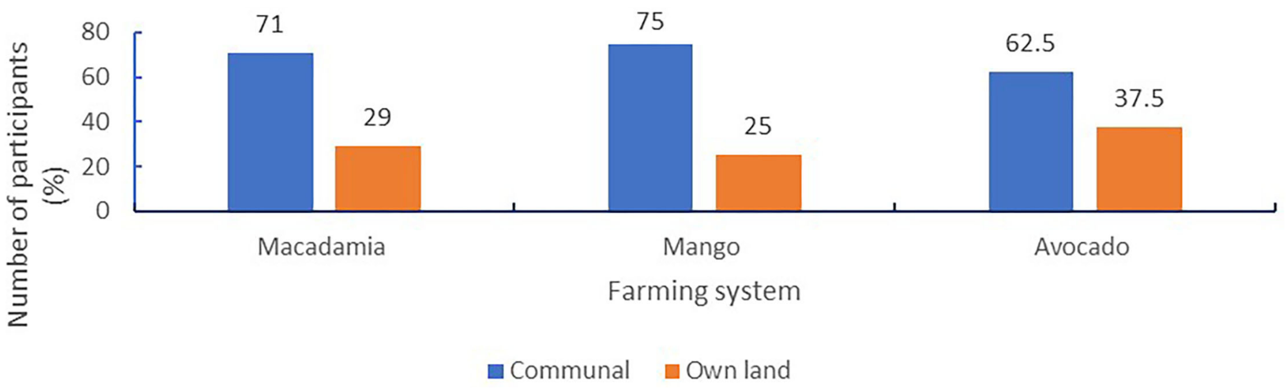

FIGURE 2 | Distribution of land ownership (%) of participants across three commodities in the study.

located in the former homelands of South Africa as indicated by Hall (2004).

Water Sources and Irrigation

The main source of water on farms was rivers (40%), dams (21%), boreholes (21%), and tanks (13%), The use of pipes was the most common form of irrigation identified amongst all participants in the study followed by rain-fed and jet irrigation (**Figure 3A**). All mango farmers reported relying on rain-fed agriculture as orchards were mature. Pipes for water reticulation were commonly used by small-scale macadamia and avocado farmers compared to jet irrigation, e.g., micro-jet and jet spray irrigation systems were commonly used by a few large-scale macadamia and avocado farmers (**Figure 3B**).

Farmers in the Vhembe district who irrigate get higher incomes from on-farm activities as opposed to dry-land farmers due to higher yields (Olofsson, 2021). Access to water for irrigation is considered a macro constraint for smallholder farmers in the Vhembe district according to Mpandeli and Maponya (2014). These farmers are often victims of water shortages and irrigation politics.

GENERAL DISCUSSION

The Significance of Small-Scale Farmers

The land issue is one of ongoing contention due the country's historic context of land distribution inequalities. Statistics show that small-holder farmers form a large percentage of farmers in South Africa at large. Aliber and Hall (2012) indicate that in 2012 there are ~2.5 million smallholder farming households in South Africa and 35,000 commercial farming units. Though there are no accurate recent statistics on the current number of smallholder farming households as this appears to be a difficult demographic to document, results of the census on commercial agriculture report in 2017 showed that commercial farming units had increased to 40,122 (Statistics South Africa (StatsSA), 2017). Due to this higher percentage of small-scale farmers any intentions of government to improve on agricultural development interventions must prioritise the need to build capacity amongst small-scale farmers.

Globally small-scale farmers generally tend to be constrained by similar problems. There are some reports from 2013 to 2020 that small-scale farmers in the Limpopo Province are faced with a plethora of challenges that compromise their capacity to be significant contributors to the provincial and national agricultural economy (Greenberg, 2013; Hall et al., 2013; Mpandeli and Maponya, 2014; Olofsson, 2018; Setshego et al., 2020; Maponya, 2021). Some of these challenges include: the inability to purchase agricultural inputs (Oni et al., 2010), transport limitations which consequently hinder market access (Mpandeli and Maponya, 2014), lack of tenure security (McCusker, 2004; Beinart and Delius, 2018), limited access to labour (Hall et al., 2013), fragmented (or no) sources of technical and financial advice (Ortmann and King, 2007) and limited access to water for irrigation (Maponya, 2021) amongst others. Government is greatly invested in the promotion of small-scale farmers to a level that allows then to compete with their commercial counterparts. This is expressed in the resolution on rural development, land reform and agrarian change (2007) where the government is quoted as saying: *"the development of the smallholder sector is thus premised on creating an enabling environment for farmers to progress in a linear trajectory toward becoming increasingly commercially oriented and finally operating as fully fledged commercial farmers thus building "a modern and competitive smallholder sector"* (ANC., 2007:22).

There have been numerous interventions by government to address the challenges of small-scale farmers in order to improve on national agricultural development some of these are outlined below with reference to the Vhembe district. This is in line with a systems analysis approach which suggests that due to the complex, multi-variable nature of a problem there cannot be only one way approach to addressing problems but a diversity of interventions (Meadows, 2008; Arnold and Wade, 2015).

Land Tenure Reform

In attempts to address the inequalities presented by a historical land distribution framework that placed small-scale farmers in

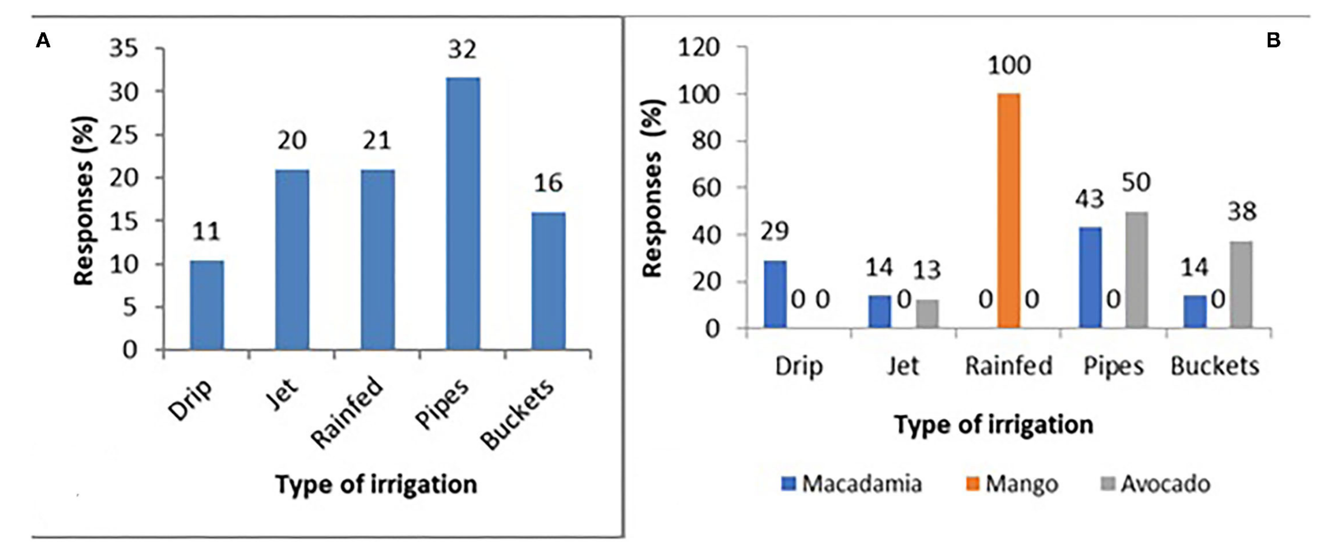

FIGURE 3 | (A) Main type of irrigation practised on farms in the study. **(B)** Main type of irrigation practised on farms in the study across commodities (*n* = 19).

a highly disadvantaged position compared to their commercial farmer counterparts, government has launched multiple policy interventions targeting land reform. Hall (2004) explains that the key focus of government's land reform has been the redistribution of land through a market-led "willing buyer, willing seller" land redistribution programme. The programme has received much criticism and current parliamentary debates around the success of this programme have been heated because it does not tie the acquisition of land to farmer support and resources to enable farmers to generate an appealing livelihood.

The lack of tenure rights for small-scale farmers in the Vhembe district much like the case of other small-scale farmers located in the former homelands is further compounded by overlapping use rights on communal land. Small-scale farmers are not able to fully participate in commercial activities because they do not own land. An example of this challenge is illustrated by Burger (2021) where a farmer may plant maize on a piece of land only to have someone else's cattle possibly graze there after the harvest and individuals from other families collecting water, food, and firewood from the same land. The same author (2021) suggests that in order to reform the current land tenure context on the communal level, the law must democratise control over communal land. This can be achieved by shifting power from the traditional leaders and placing it in the hands of community members. The challenge of land reform and the absence of tenure security is not unique to South Africa. Peters (2009) draws our attention to the fact that communal tenure is *"the joint creation of colonial officials and African leaders"* and therefore a complex problem that impact numerous African countries.

Using the example of Kenya, the post-colonial government's approach has been the creation of settlement schemes. According to Rutten et al. (1997) Kenyan land use policy was primarily targeted at adjudication and replacing customary land rights with individual tenure agreements. This approach was aimed at facilitating collateral for loans and enabling long-term investments. Unfortunately, one of the many negative consequences of this attempt at land reform has been the creation of a category of landless people as land has become increasingly concentrated in the hands of a privileged few. This sheds some light on the complex challenge that land reform presents for many governments in other African countries. It also presents an opportunity for the adoption of a systems analysis approach to address these complex problems.

The Commodity-Focused Approach

There has been a growing trend in agricultural policy toward a commodity-focused approach to agricultural development (Chawiche, 2015; Jaskiewicz, 2015; de Satgé and Phuhlisani, 2020). Olofsson (2018) draws our attention to how a commodity focus can be seen amongst small-scale farmers in the Vhembe district. Olofsson (2018) maintains that it is particularly visible amongst macadamia and avocado farmers where the focus has shifted entirely toward integrating small-scale farmers into national and international markets. This commodity-focused approach is also exemplified in agricultural extension in the district. Extension officers are aligned to a specific commodity specialisation and provide support and training to farmers who are grouped according to their production focus (Aliber et al., 2010; Genis, 2012). Olofsson (2018) dates the rapid growth in orchards for avocado, mango and macadamia nuts in the Vhembe district to the first decade after the transition to democracy in 1994.

Another result of this commodity-focused approach has been the expanding role for commodity organisations in supporting small-scale farmers (Aliber and Hall, 2012). This has been especially evident in the activity of the South African Subtropical Growers Association (Subtrop) and the South African Macadamia Growers Association (SAMAC). Both organisations, which historically represented white commercial farmers in the region, have taken an active role in supporting small-scale farmers who produce avocados and macadamia nuts in recent years (Maponya, 2021). According to DAFF (2014) a statutory levy was implemented in 2014, of which 20% of the revenues were earmarked for small-scale "transformation" amounting to approximately R2 million in the first 4-year period. Most of this money was spent on enterprise development of small-scale macadamia farmers.

Access to Capital for Small-Scale Farmers

There are a few approaches that the government has used to finance the buying of land for emerging black farmers that have included access to both loans and grant funding. One such approach was the Land Grant which was put into operation in 1995 in the earliest years of South Africa's democracy. The Land Grant operated through the Settlement Land Acquisition Grant (SLAG). Through this grant the government provided a grant of R15 000 per beneficiary household to buy land that would be registered as a property, with up to 500 families registered as beneficiaries (Aliber and Hall, 2012). Hall et al. (2013) argues that while it stands to reason that concentrating resources on smaller numbers of beneficiaries and projects is a means of improving the "quality" of those particular projects, it is obviously at the expense of reaching larger numbers of farmers thus highlighting a shortfall of the scheme.

Greenberg (2013) indicates that the Land Bank's lending activities are split between business and corporate banking, retail commercial and retail emerging market. The retail emerging market is said to be for small-scale farmers "without a good credit profile." In 2011 the CEO of Land Bank, Phakamani Hadebe indicated that up to R1 bn would go to emerging farmers over 2 years under the Retail Emerging Market unit (Vollgraaff, 2011). More recently the Land Bank 2019 annual report indicates that the absolute value of "transformational loans" targeted at small-scale farmers has increased to R7.9 billion representing 17% of the loan book, up from 12% in 2018.

A Shift From "Small-Scale" to "Commercial"

Literature identifies a small cluster of small-scale farmers who are characterised by their larger scale of production, high reliance on hired labour and higher level of mechanisation in comparison to other small-scale farmers (Hall et al., 2013; Olofsson, 2018). These have been coined differently by various authors as *"small-scale capitalists"* (Olofsson, 2018), *"emerging commercial farmers"* (Whitbread et al., 2011), or *"emerging farmers"* (Senyolo et al., 2009). This small cluster of farmers has higher land access compared to other small-scale farmers with a median of 40 ha, ranging from 22 to 54 ha, as compared to other small-scale farmers who averaged between 5 and 7 ha according to a study by Olofsson (2018). It is commonplace in South African policy and planning documents to use the term smallholder and "emerging" farmer synonymously (DAFF, 2012, 2013, 2014) suggesting they are not a category of farmers in their own right but in a process of becoming a category. Non-farm employment plays an essential role in sustaining and developing the farm in the years leading up to full production for farmers who form part of this small cluster.

Non-farm Income

Marinus et al. (2022) highlight the value of diversification of livelihoods to improve the living income of small-scale farmers in Africa. Non-farm income, livestock and vegetable farming rank high amongst examples of additional income sources that have proven successful for smallholder farmers in Sub-Saharan Africa. Olofsson (2018) identified the most common form of non-farm employment amongst small-scale farmers in the Vhembe district as teaching, at primary and secondary school levels. According to Genis (2012) dependency on non-farm employment allows farmers to reinvest profits. In as much as non-farm income may serve as beneficial for small-scale farmers as it facilitates capitalisation, it can also result in these farmers being marginalised and excluded from accessing information, training and other state or private sector opportunities premised on the expectation that one is a full-time farmer and therefore available during working hours (Aliber and Hall, 2012). This has created an opportunity for white commercial farmers to emerge as *"knowledge brokers"* (Olofsson, 2018:52) providing access to alternative resources and facilitating social relations across racial and class barriers and fostering interaction between large and small-scale farmers.

According to Aliber and Hall (2012), small-scale farmers in Limpopo have resorted to employing innovative strategies to optimise their potential to participate in the market value chain in a manner similar to large-scale commercial farmers. Some of these strategies include the use of intercropping systems. Using the example of tree-crop small-scale farmers in the Vhembe district, Olofsson (2018) illustrates how annual tree-crop income constitutes the main agricultural income. A very small share of this agricultural income is obtained from a variety of crops such as sweet potatoes, spinach, carrots, tomatoes, peppers, ground nuts and cabbage amongst others. These are mostly for home consumption and only surplus is sold to local markets generating small amounts of money. Non-tree crops are perceived to be a short-term strategy for income generation while tree crops reach maturity which can take between 2 and 4 years.

CONCLUSION AND RECOMMENDATIONS

In order for the South African government to successfully achieve the agenda of agricultural development, taking into account the dual nature of the country's farming systems and the varied ways in which they respond to the drivers of production there is need for multiple points of intervention. There is an urgent need to focus attention on capacitating small-scale farmers to be able to compete on similar terms as large-scale commercial farmers while sustaining a decent standard of living. Research and policy development priorities need to adopt a systems thinking approach which highlights the complexity of the interrelatedness of the factors that impact the drivers of production and the practicality of therefore applying interventions concurrently. There is potential for systems approach to be applied to a broader context beyond South Africa and in other sectors. Issues surrounding farming systems are closely tied to the sustainable development goals (SDG) 1 (no poverty) and 2 (zero hunger) but a systems analysis approach can be applied to tackle other issues encapsulated in the remaining SDGs that intersect across different spheres.

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FM and MS contributed to conception and design of the study on which the manuscript is based. FM wrote the first draft of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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A Water-Centric Approach in the Assessment and Governance of the Water-Energy-Climate Change Nexus in South Africa

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Water and energy interdependency, in the context of climate change, threatens security of these resources. Anecdotal evidence suggests that risks associated with the "Water-Energy-Climate Change" (WECC) nexus will affect all subsectors of the economy. Yet the WECC nexus has not received commensurate attention in research and policy. Some countries have begun identifying avenues to understand and forestall WECC impacts, but less so in developing countries. This has compromised the adaptive capacity and resilience of developing countries' economies to WECC impacts. This paper analyses existing literature, historical and contemporary secondary data on climate change, water and energy interdependency in South Africa. It outlines the interlinkages and implications of these three components on each other, particularly within the discourse of sustainable water resource management. The paper recommends water-centric approaches to improve evidence-based institutional and policy frameworks to address the myriad challenges of this nexus in a holistic and integrated manner.

Keywords: water, energy, climate change, nexus, South Africa

INTRODUCTION

The constant supply of water and energy resources has become an absolute imperative for sustaining modern life. Intensified need for these resources in socio-economic development programs has resulted in an exponential increase in their demand at global, regional, national and local levels (Hussey and Pittock, 2012; Sparks et al., 2014; Carpenter, 2015). The supply of water and energy has, however, became quite complex, given the influence of factors such as rapid population growth, increased food production and consumption, and economic development, all of which combine to result in high demand for these resources in a context characterized by the emergence of climate change and associated environmental stresses. The supply of these resources, together with the need to address climate change, has emerged as one of the central issues for discussion among sustainable development researchers and policy makers. These debates have become topical as suggestions emerge on how the water, energy, and climate change elements relate to each other and how they influences socio-economic issues, resulting in the concept of the Water-Energy-Climate Change (WECC) nexus (Cammerman, 2009; Head and Cammerman, 2010). Anecdotal evidence suggests that the existence of WECC impedes the attainment of environmental and socio-economic goals for communities across the world, hence the need for management of the challenges arising from this nexus. There is, therefore, an urgent need for the development of resilient and adaptive strategies to mitigate the impact of WECC on Sustainable Development Goals (SDGs), particularly the SDGs, 6, 7, and 13.

As demand increases for measures to ensure sustainable water and energy supply while simultaneously combating climate change, contemporary evidence suggests that the understanding of how WECC components are interlinked is limited. This knowledge gap is reflected mainly in the current segmented policy development and planning approaches for addressing water, energy, and climate change challenges–weaknesses that are aggravated by a lack of integration and limited application of analytical tools to manage these WECC components (Bizikova et al., 2013; Rasul and Sharma, 2015; Pahl-Wostl et al., 2018; Gobin et al., 2019). These planning and policy segmentations are common in developing and middle-income countries such as those in Sub-Saharan Africa (SSA). This has resulted in minimal progress toward implementing the principles of sustainable ecological and socio-economic development in the region. While there is a need for coordinated and holistic planning for management of WECC risks and opportunities, approaches should be based on sound empirical evidence and a clear understanding of the interfaces between water, energy, and climate change.

In South Africa, the country's National Developmental Plans (NDP) envisage the reliable supply of water and energy resources under combatted climate impact. Mathetsa et al. (2019) argued that South Africa is prone to the realities of the WECC nexus and its associated repercussions. For instance, the country's energy production system is centralized on water reliant fossil-fuel burning technology, which contributes significantly to climate change through the release of Greenhouse Gases (GHGs). In the same vein, climate change, together with the current reliance on water-intensive energy generation processes to address electricity demands will exert additional pressure on constrained water resources in the country. The current water and energy supply constraints, together with the growing need to address climate changes, impose critical challenges on the attainment of national development plans in South Africa (World Bank, 2017). This raises a need for the country to strengthen analysis and understanding of WECC locally to ensure the development of effective strategies for addressing the risks related to this nexus. As is the case in most developing and some developed countries, South Africa's fragmented approach to planning and policy development on energy, water and climate change is one of the key barriers to the effective integration of these sectors (Prasad et al., 2012; Mabhaudhi et al., 2016; Nhamo et al., 2018; Mathetsa et al., 2019). This is despite internal reforms implemented within each of these sectors. It is against the background of these challenges and inadequacies that the need for a comprehensive understanding of WECC and the promotion of a sectorally integrated and effective management approach be emphasized.

Assessment of existing literature and empirical data is crucial for understanding the interfaces between the WECC components. For instance, empirical approaches that allow for the collection, analysis and presentation of data on these components over a chosen period enable an improved understanding of the WECC interdependencies thus allowing the utilization of such physical data is critical for providing vital knowledge for decision-making on issues related to different nexus configurations (Bless et al., 2013; Liu et al., 2017; Aboelgna et al., 2018). Such knowledge can only be attained where there are systems that enable the collection, availability, accessibility, and usability of data. However, there is a lack of such systems across the globe particularly in the less-economically developed regions of the world. In SSA, for example, Yillia (2019) argued that broadened understanding and progress toward nexus integration are hindered by a lack of information or data, particularly at the grassroots level where most activities are undertaken. Similarly, in South Africa, the unavailability of data and information is one of the causes of the current policy fragmentation and emergent nexus risks (Gobin et al., 2019). This observation suggests the urgent need for South Africa to utilize physical data analysis as one of the key tools for understanding the interactions between water and energy resources, and climate change. Understanding these concurrent interactions will likely promote an integrated approach toward addressing the risks and opportunities emanating from the WECC nexus.

A water-centric approach is one of the most pertinent amongst the different existing methods for analyzing the complexities of the WECC nexus (Cammerman, 2009; Bizikova et al., 2014; McCartney and Brunner, 2020). While this perspective should not promote water governance above other sectoral approaches, the importance of water across different systems suggests that sustainable management of these resources is critical for addressing nexus challenges. Against this background, Head and Cammerman (2010) argue that holistic, coordinated and informative management of the WECC nexus can adopt water-related approaches such as the Integrated Water Resources Management (IWRM) Framework. This framework holistically addresses complex systems that connect water and related resources such as energy and food (Global Water Partnership, 2000; Fatch, 2009; Fulazzaky, 2014). In South Africa, the rationale for applying water-centric approaches such as IWRM in managing WECC is motivated by the dire status of water resources in the country, a situation that is predicted to worsen with serious impacts on related resources and other sectors such as energy and agriculture, respectively. Moreover, existing literature shows how water limitations experienced in the several countries necessitate the adoption of the IWRM approach for understanding and managing WECC, particularly within the context of water being a finite resource (Cammerman, 2009). Based on the preceding arguments, this paper uses existing literature and secondary data obtained from different stakeholders to validate/quantify the relationship that water has with energy and climate change sectors in South Africa. The paper articulates the significance and relevance of a water-centric approach to Assessing and understanding WECC issues. The paper concludes with recommendations on actions that could enhance the promotion of integrated WECC management in South Africa.

THE IWRM AS A FRAMEWORK TO ANALYSE THE WECC NEXUS IN SOUTH AFRICA

Studies in the recent past explored the significant role that the nexus has on achieving the sustainable development goals (SDGs). A number of these studies have, mainly focused on the inextricable linkage between key resources of water, energy, and food, resulting in the configurations of Water-Energy (WE) and Water-Energy-Food (WEF) (Prasad et al., 2012; Gulati et al., 2013; Carter and Gulati, 2014; Cullis et al., 2018). Several studies define the nexus as a tool that promotes synergies and trade-off of water, energy and food systems, thus guiding coordinated and integrated approaches for formulating development policy and for the purposes of ensuring resource efficiency and optimization (Albrecht et al., 2008; Mathetsa et al., 2019; Pahl-Wostl et al., 2020). Given the rising need to equally address the water, energy and food constrains, development of contemporary, integrated and analytical measures becomes imperative to ensure security of these resources. The assessment of the interlinkages of the nexus and the development of such approaches to understand and measure their interactions, could probably be executed by way of employing a sectoral approach and creating an inventory of resource relationships. Several scholarly literature suggests approaches that are within a water-centric system and which can potentially be used to analyse the resource efficiencies embedded within the nexus discourse (Cammerman, 2009; Mathetsa et al., 2019; McCartney and Brunner, 2020). From a point of view therefore, we can argue that the nexus approach can potentially offer a framework through which to comprehensively understand and manage the social and economic implications it has in water-stressed countries such as South Africa. It is against these observations that in this paper we assess the nexus in the context of IWRM Framework, an approach highly regarded as suitable for promoting sustainable water resource management. Selection of the framework is triggered by the fact that South Africa is the 30th driest country in the world and has had devastating impacts from water scarcity (Carpenter, 2015; Mathetsa et al., 2019).

Although several scholars define IWRM differently, its primary goal remains the promotion of sustainable water resources management. Global Water Partnership (2000), for example, define the IWRM as "a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems". This definition is embedded in the need for coordinated and effective management of all aspects of surface and groundwater and their hydrological boundaries, as well as "related resources," depending on or influencing water availability. In this case, water-dependence sectors such as food production, energy generation, domestic utilization and climatic variables change highlight key interactions between human-induced processes and water (Funke et al., 2007; Bindra et al., 2014). It is argued that while IWRM should not be viewed as a replacement for policy, its principles facilitate the development of strategies, tools or management guidelines, thus initiating sustainable water resource management. The successes of this framework are based on its ability to coordinate the management of water resources and associated activities in a holistic and risk-based manner (Global Water Partnership, 2000; Leendertse et al., 2008; Fulazzaky, 2014). This is despite its documented shortcomings such as lack of innovative approaches (Biswas, 2008).

Implementation of IWRM has been key in water sector reform processes in South Africa. For instance, application of the IWRM framework is integral to post-apartheid administrative tools such as the National Water Act (Act No. 36 of 1998) and the National Water Resource Strategy, which was designed to enhance sustainable and equitable water resources management and use at both national and catchment levels [Department of Water and Sanitation (DWS), 2004, 2014; Pollard and Du Toit, 2008]. The application of this framework in some parts of South Africa has, however, not been effective particularly at ground level. Claasen (2013) attributes this inconsistency to various factors, which include limited experience and lack of information, inadequate capacity and inability to innovate among various stakeholders. These inadequacies are cause for serious concern, as is the ineffective management of water resources at the grassroots level and the potential impact it has on water security and other sectors.

While the application of IWRM is mainly on water resources management, Cammerman (2009) and Fulazzaky (2014) suggest that this framework can be considered as a tool for management of other complex systems, particularly those prompted or generated by human interaction with nature. The WECC nexus provides a good example of a complex system amenable to the application of the IWRM framework as it elaborates the inextricable linkages between water, energy and climate change–elements that are closely linked to human activities. Moreover, such a framework allows for the consideration and incorporation of other relevant disciplines and stakeholders in ensuring sustainability, equity, and efficiency, not only in the water sector but in other sectors as well (Bindra et al., 2014). Centralizing WECC arguments based on water-related information, therefore, enable promotion of integrated management of this nexus.

As stated, the pronounced interdependence of water and energy resources, both of which are finite, presents systematic challenges on how to address socio-economic developmental needs. Of the two, water resource security has been more scrutinized because of its intimate linkage to climate change and the limit in terms of alternatives to water. Within SSA, South Africa is an example of a country with water resource predicament in several ways. First, it is semi-arid, with low rainfall, and deteriorating water quality due to anthropogenic activities and over allocation, suggesting that the country's water resources are undoubtedly finite. Secondly, South Africa's vulnerability to climate change exacerbates its water insecurity. Last, water plays a critical role in various sectors of the country's economy, including in energy and food production, which means the country faces the urgent need for development of effective adaptation and mitigation measures to ensure sustainable use and the protection of limited water resources.

Furthermore, the water resources constraints in South Africa are aggravated by the current administrative tools' inability to address emerging risks and opportunities, thus hindering attainment of national developmental endevours [Department of Water and Sanitation (DWS), 2014]. This is likely to influence governance of multiple systems that incorporate or interact with water resource dynamics thereby affecting the attainment of the country's NDPs. It is therefore important to understand the water user-use relationship. In this study, large freshwater users such as the energy generation and agriculture sectors are considered significant to management of water resources. Therefore, the concept of water as a finite resource is among the key themes used for analysis of the risks associated with WECC. This perspective is aligned to the proposition by Funke et al. (2007) that South Africa should adopt an inclusive approach to the management of water resources, which considers all hydrological cycles and water's interactions with other resources and the ecosystem as a whole. This study, therefore, emphasizes the need to acknowledge the IWRM principle that calls for the full recognition of the finite and indispensable nature of freshwater resources in the coordinated governance of the nexus.

METHODOLOGY

The study applied different approaches to attain its objectives. Firstly, a rapid appraisal of the literature on the nexus subject was conducted. Both Scopus and Google Scholar were used to search for the words "water", "energy", "food", "climate change", "nexus" and IWRM in the abstract, title and keywords. The search resulted in approximately 250 peer-reviewed articles. In addition, tools and methods for the nexus application developed by non-governmental or inter-governmental research and policy institutions (e.g., FAO, WRC, IPCC, DWS, and DEA) were used to supplement the literature reviewed. Articles and reports meeting the following criteria were used: (1) they employ the nexus concept in terms of natural resource sustainability; (2) they include all four sectors of water, energy, food and climate change, and (3). they outline methodologies or analytical tools to assess the nexus studies, and (4). The IWRM successes and failures are defined. After a rapid appraisal of the 250 articles, 36 articles were classified as "methodological", 82 were "conceptual", while the remaining 132 were excluded from the study as they did not met the above defined criterion. The selected articles and reports were further analyzed using a meta-analysis technique and they form the basis of the current paper.

Secondly, the study adopted a quantitative approach to assess the water, energy and climate change relationships within the context of South Africa. Several scholars have suggested that the discussions and interpretations on the WECC configurations are more strengthened and informative when the nexus is assessed within the discourses of both physical and social measurements (Liu et al., 2017; Aboelgna et al., 2018). This approach was chosen based on views in the literature that assert that the assessment of nexus configurations can be streamlined by using statistical methods to quantify the interlinkages (Cammerman, 2009; Bless et al., 2013; de Strasser et al., 2016; Aboelgna et al., 2018). This approach was used to particularly to quantify the qualitative data in order to comprehensively understand the interactive role that water, a finite resource in South Africa, has with both the energy and climate change systems.

The study analyzed secondary data from sectors that play a key role in the management of climate change, and energy and water resources in South Africa. Purposive sampling was used to select sources for data collection from these key sectors and relevant departments. This sampling method involves the deliberate identification and selection of role players who are knowledgeable in the subject and context under study as key informants to provide data from these key sectors/departments (Etikan et al., 2016).

The power utility Eskom, the South African Weather Services (SAWS), Water Service Providers (Municipality and Rand Water), the Departments of Water and Sanitation (DWS) and Environmental Affairs (DEA) were selected as sources from which sector-specific data would be sourced. Data was mainly collected from the power generation regions of Waterberg and Highveld, as illustrated in **Figures 1**, **2**. Data collection was enhanced by a snowball technique where referrals were used to ensure data is obtained from relevant personnel within the selected sectors. This resulted in interviews with key data management personnel who also supplied secondary data in excel format. As illustrated in **Table 1**, secondary data collected from Eskom and SAWS was of primary significance in generating information used for the study, while data from the other sources was mainly used for appraisal purposes. The sourced data was predominantly generated from the Waterberg and Highveld regions, which are both major locations of coal-fired energy generation technology in South Africa.

Data from 2008 to 2018 was analyzed using descriptive statistical analysis. Application of the method resulted in interpretative graphs derived from the mean values attained from the data, thus highlighting the key points at which water conversely interacted with energy and climate change. The analysis enabled the understanding and subsequent discussion of WECC nexus complexities and their interdependencies.

RESULTS AND DISCUSSION

The collected data allowed for the assessment of the water-energy; energy-climate change; and climate change-water nexus interfaces. The deliberations adopted the water-centric approach to enable understanding of the complex WECC nexus in South Africa.

Converse Water-Energy Interchange

Coal combustion, which requires water as a key input, accounts for approximately 70% of energy generation globally (Carpenter, 2015). It is established that nearly 75% of freshwater withdrawals are used solely for electricity generation processes, particularly coal-combustion technology (Cammerman, 2009; Carpenter, 2015). In South Africa, approximately 85% of energy is generated from coal-combustion, thus exerting enormous pressure on the supply of water resources. **Figure 3** shows the severity and magnitude of water usage at the power generation stations in the

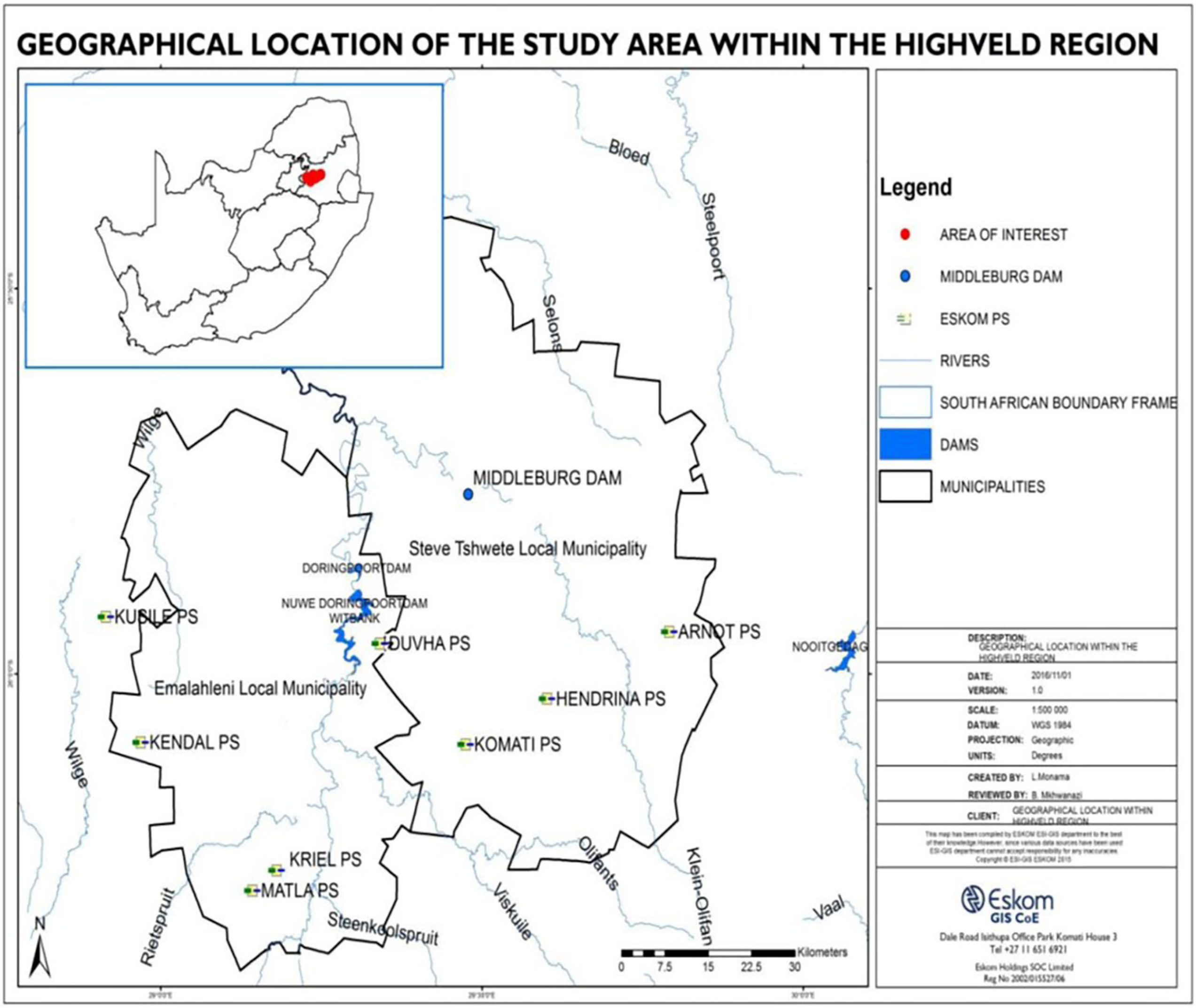

FIGURE 1 | Geographical location of the Power Stations at Highveld region, South Africa. Data Source: Eskom (2019).

Highveld and Waterberg regions of South Africa. These power plants contribute approximately 32,000 megawatts (MW) of the country's total electricity generation installed capacity of 45,000 MW. **Figure 3** also draws a comparison of the amount of water, in liters (l), used to produce Kilowatt per hour Send Out (KWhSO) electricity from each region between the years 2008 to 2018.

It is evident from **Figure 3** that the power plants in the Highveld region consume more water than those in the Waterberg. In 2008, for example, the Highveld power plants to generate 1 KWhSO compared to 0.1 l /KWhSO in the Waterberg stations used 3.5 l. On average, Highveld power plants utilized 2 l/KWhSO more than those in the Waterberg did over the 11-year period for which records were analyzed. This is influenced by significant variances at the Highveld power plants between 2008 and 2010, and at the Waterberg stations between 2014 to 2016. For example, Eskom (2019) highlights that addition and reduction of generating units between 2008 and 2011 was a contributing factor in the observed variances in water consumption. While **Figure 1** highlights the significant role of water use in electricity generation, the quantity of water required is influenced by several factors. First, is the capacity of power plants. For example, the power plants in the Highveld have an installed capacity of approximately 24,000 MW, compared to the 8,000 MW capacity in the Waterberg. The power plants in the Highveld therefore use more water in their generation processes. The second factor influencing water consumption is the technology applied in each power plant. All power plants in the Waterberg employ a dry-cooled process in contrast to six of the eight in the Highveld, with the remaining two being dry-cooled. Both technologies, however, do rely on water. The dry-cooling power generation process consumes approximately 15% less water than wet-cooled power generation (Pather, 2004;

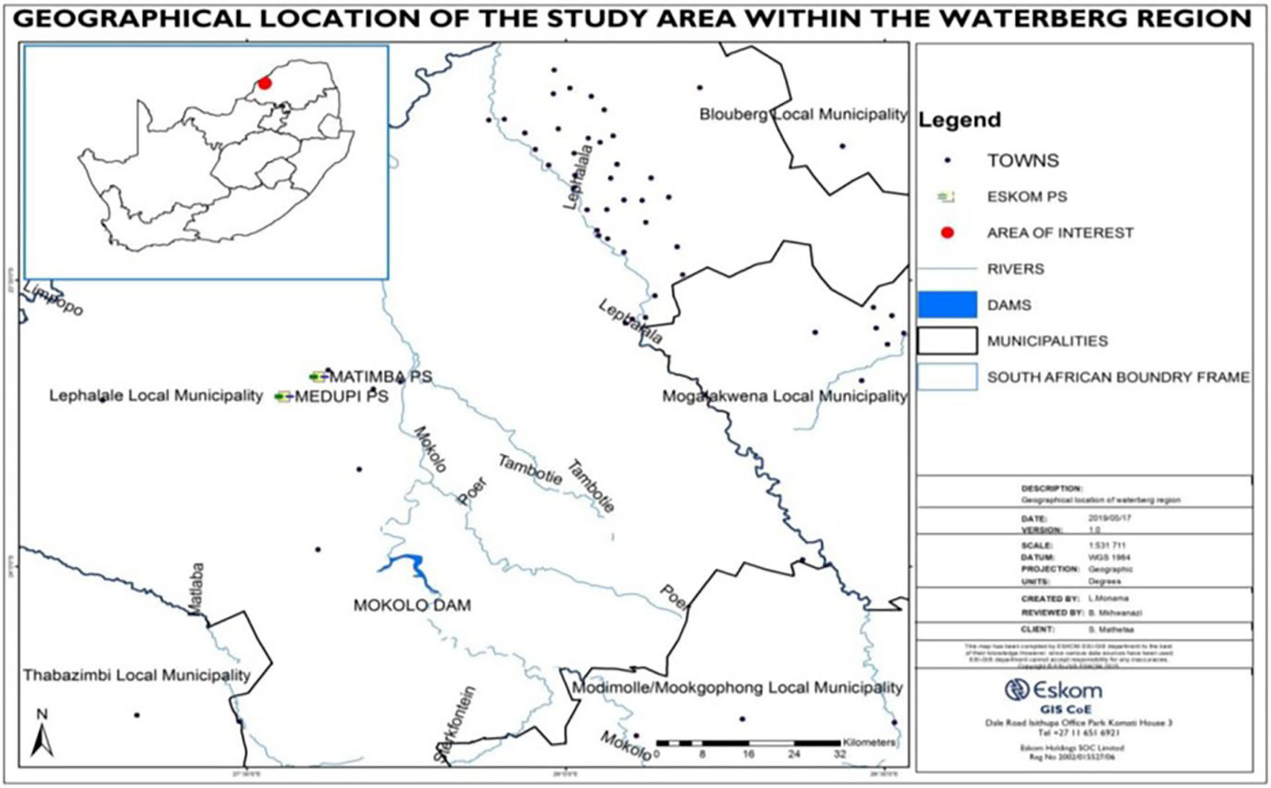

FIGURE 2 | Geographical location of the Power Stations at Waterberg Region, South Africa. Data Source: Eskom (2019).

TABLE 1 | Sources of data.

Organization	Role in WECC nexus	Data format	Data verification process
Eskom	Owns and operates power plants in South Africa to ensure electricity supply.	>.Xls (spreadsheet) on water consumption vs energy produced 2008–2018. >.link to GHG emissions 2008–2018.	Eskom internal and external verification processes such as audits.
South African Weather Services (SAWS)	Operates weather stations countrywide to ensure the provision of climate services.	>.Xls (spreadsheet) on Highveld and Waterberg regions rainfall vs. temperature 2008–2018.	SAWS internal procedure on the maintenance of measuring equipment and software.

Cullis et al., 2018). This high demand for water in electricity generation has pushed the country toward the building of dry-cooled power plants post the 1980s [Department of Water and Sanitation (DWS), 2014].

The water needs for electricity generation resulted in categorization of the energy sector as a "strategic water user" with a high assurance of 2% freshwater allocation. However, the sector remains vulnerable due to the current and projected freshwater shortages in the country, which threatens energy security. The vulnerability of the energy sector to freshwater shortages has resulted in supply to the power plants in the Highveld region being maintained through water imports from pristine catchments such as Usuthu and Inkomati. Furthermore, the country has adopted strategies and initiatives such as the Mokolo-Crocodile Augmentation Process and the Lesotho Highlands Water Project to avert shortages in water constrained regions such as the Waterberg. These strategies have thus elevated the current and projected freshwater withdrawals for energy and other sectors such as agriculture and domestic consumption.

The contribution of the energy sector to the water value chain is equally important. Approximately 3% of the energy produced globally is consumed by water related processes, and in South Africa, this consumption is the third largest in the world (South African Cities Network, 2014; Gobin et al., 2019). Mainly the rising population, industrialization, urbanization, and pollution drive the increasing demand for energy in the water and wastewater treatment industry in the country. Moreover, the long distance between water sources and intended users increases the

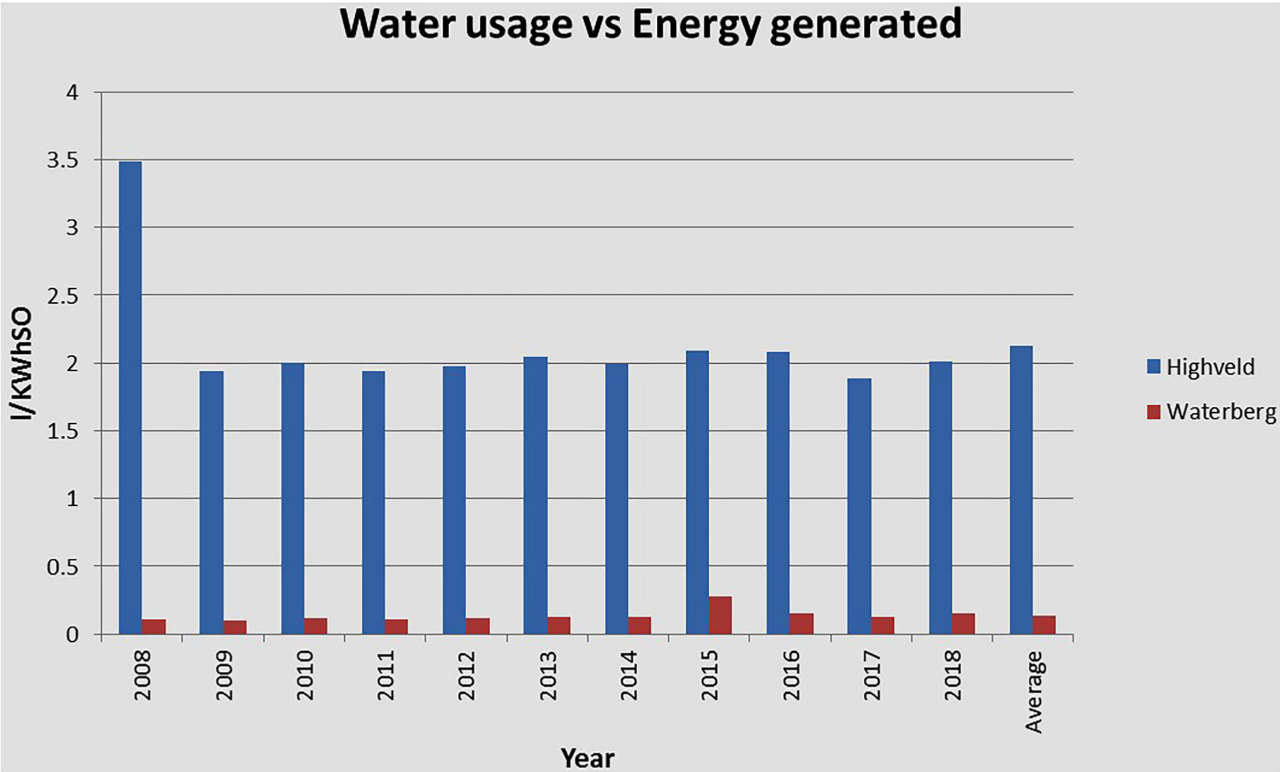

FIGURE 3 | Water used per Kilowatt per hour Sent Out for the Highveld and Waterberg stations. Source: Data from Eskom (2019).

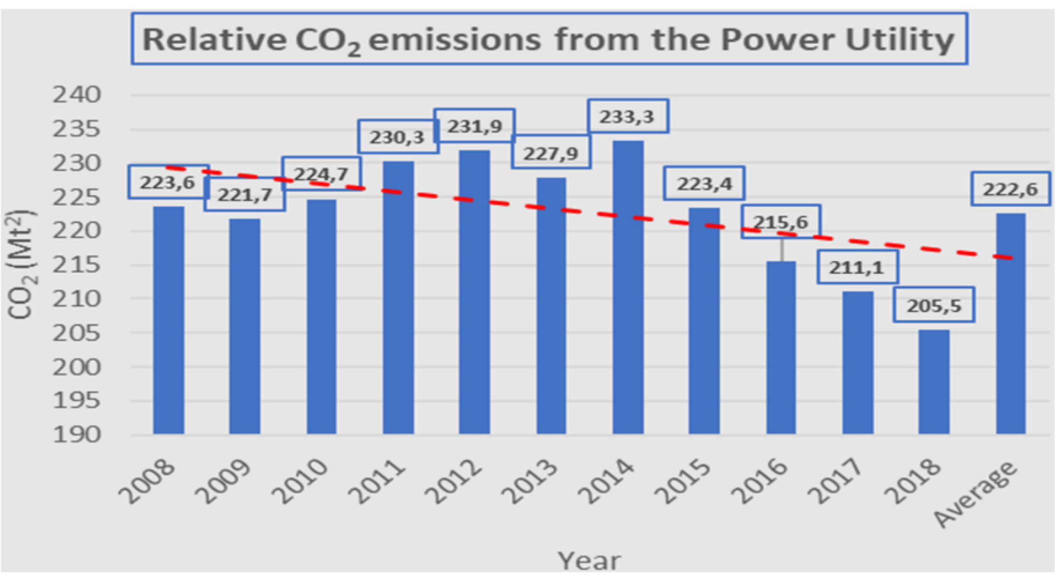

FIGURE 4 | Relative CO_2 produced during fuel-burning electricity generation. Source: Data from Eskom (2019).

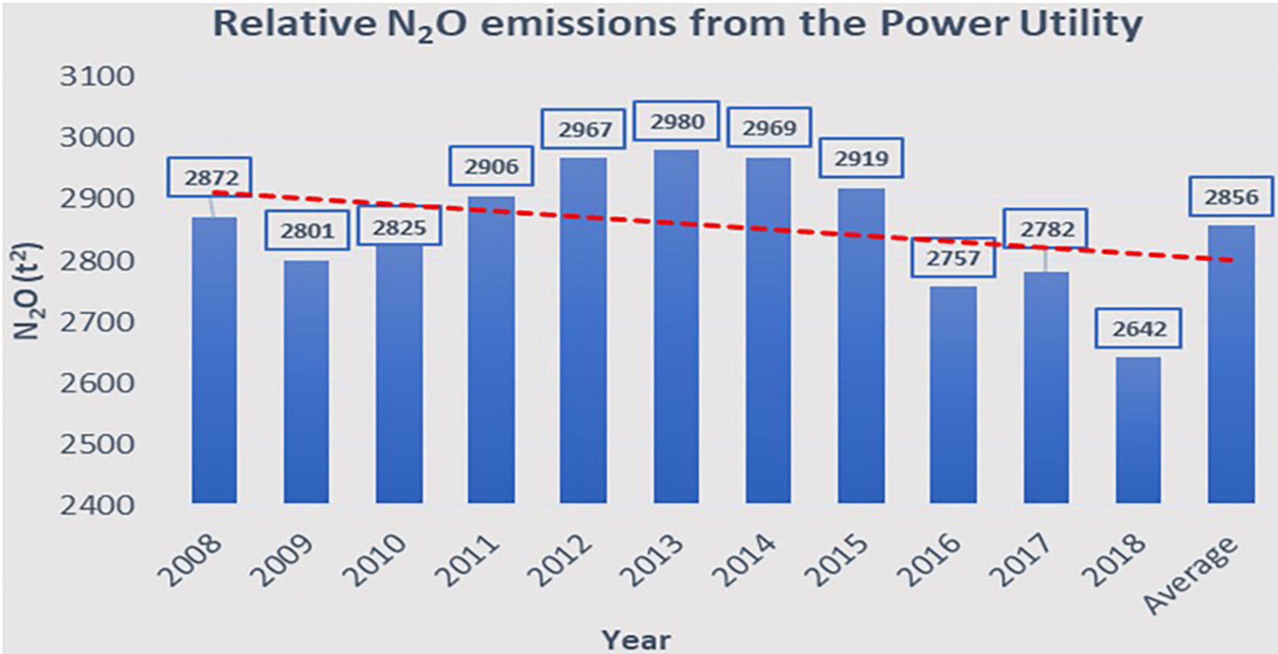

FIGURE 5 | Relative N_2O produced during fuel-burning electricity generation process. Source: Data from Eskom (2019).

energy needed for pumping and treatment (Cullis et al., 2018). Despite the importance of this subject globally, information related to energy usage in the water value chain is hard to come by and difficult to maintain due to a variety of factors. These include the fact that there is a wide variety of water users, while water usage also varies in several sectors, which include domestic, industrial and other sectors (Liu et al., 2017). In a few cases, however, countries such as the United States and Australia have effectively quantified the energy needed for their water supply value chain (abstraction, treatment and distribution) to inform their planning processes (Cammerman, 2009; Carpenter, 2015).

In South Africa, the present study has identified data collection and accessibility challenges in relation to the energy-water interface. For instance, data on energy utilized for water and wastewater treatment is rarely quantified or made available by key institutions such as water service providers and municipalities. This creates a scenario where institutions develop policies and strategies that are misaligned and serious deficiencies in governance processes on water and energy management. This finding calls for key role players in the energy and water supply value chain to urgently address the data collection and accessibility gaps.

Energy-Climate Change Relationship

The energy sector's contribution to climate change is a global challenge. This is particularly so I relation to GHG emissions from coal combustion [Intergovernmental Panel on Climate Change (IPCC), 2014; Carpenter, 2015]. **Figures 4, 5** show the relative amount of carbon dioxide (CO_2) and nitrous oxide (N_20) observed at coal-fired power plants, with minimal contribution from Open Cycle Gas Turbines (OCGT). In South Africa, for example, coal combustion is currently the most reliable source of energy, and yet it contributes significantly toward GHG emissions (Seymore et al., 2014; Cullis et al., 2018). The difference in the emissions from these two electricity-generating technologies is due to the higher output of GHGs from coal combustion as compared to OCGT and the predominance of coal combustion for electricity production. Eskom (2019) states that OCTG usage is minimal and it comes online only when supply from coal-fired power plants is severely constrained.

Department of Environmental Affairs (DEA) (2015) indicates that CO_2 emissions in South Africa are largely due to contributions from the energy sector. An average of 222.6 Mt2 CO_2 was emitted annually between 2008 and 2018, with the highest concentrations of 233.3 Mt^2 recorded in 2014. However, there was a steady decrease in the CO_2 emitted annually from 2014 to 2018. This corresponds with the decline of 0.04% CO_2 emissions recorded from the energy sector since 2012 [Department of Environmental Affairs (DEA), 2015]. Similarly, the energy sector emits high concentrations of N_2O. For example, it is illustrated in **Figure 5** that the average annual N_2O concentrations from coal combustion electricity generation was 2,865 t^2 between 2008 and 2018, with the highest relative figure of 2,980 t^2 recorded in 2013.

These findings are clear evidence of the contribution of the country's energy sector to GHG emissions. The decline in the release of CO_2 and N_2O, however, is an indication of the efforts being made to manage these emissions, and this could be attributed to the improved policy context and awareness of the impact of climate change on natural and socioeconomic resources, particularly on finite water resources.

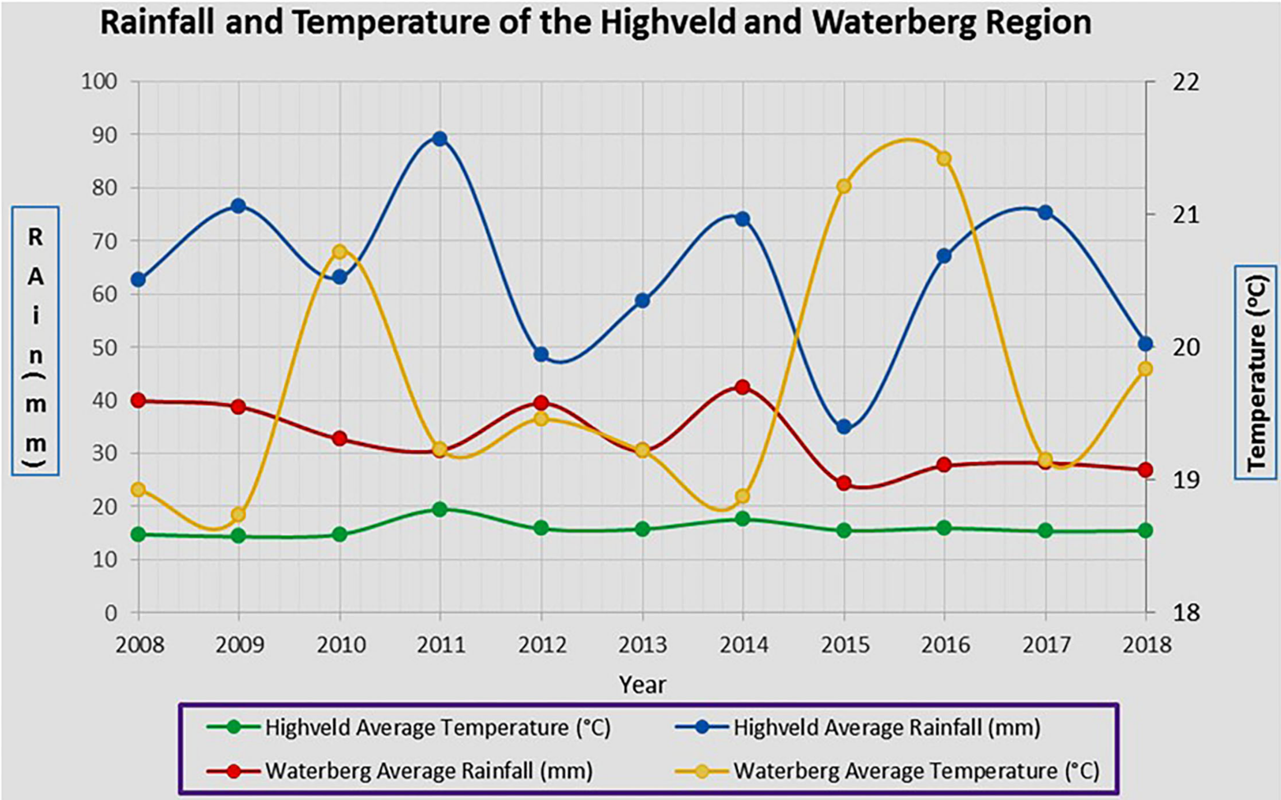

FIGURE 6 | Comparison of the temperature and rainfall interactions. Source: Data from South African Weather Services (SAWS) (2019).

Water-Climate Change Relationship

The impact of climate change on water resource availability is widely recognized (Hejazi et al., 2014; Carpenter, 2015; Gobin et al., 2019; Mathetsa et al., 2019). Key drivers of the hydrological cycle include climate change-related factors, such as high temperature and moisture conditions, which, in turn, influence water availability. In South Africa, climate change-related extreme hydrological events such as prolonged droughts, floods and intensified rainfall already occur quite regularly (Nkhonjera, 2017; Mathetsa et al., 2019). **Figure 6** shows the relationship between temperature and rainfall, thus water availability, in the Highveld and Waterberg regions. It is evident that the Waterberg experiences higher and more variable temperatures than the Highveld. For example, the Waterberg recorded highly fluctuating temperature profiles for two reporting periods of 2009 to 2011 and 2014 to 2017 while the Highveld remained mainly constant throughout the period 2008 to 2018. The temperature data supports an observation by Eskom (2012) that the Waterberg is among the regions expected to experience significant warming resulting from climate change impacts.

Furthermore, **Figure 6** shows how the varying rainfall patterns in each region are influenced by respective temperature profiles. For example, the Highveld recorded lower temperatures and high, varying, rainfall patterns. This is contrary to the higher temperatures and lower, constant, rainfall recorded in the Waterberg region. The average rainfall in each region, however, remains lower than the country's annual average of 495 mm. This observation supports the assertion by Mukheibir (2008) that inland temperature is expected to increase by ∼2–3°C compared to the 1.5°C increase expected in the coastal areas, thus lowering the region's precipitation intensity, frequency, and duration. Whereas the unpredictable variations and increased rainfall intensities will exert pressure the finite water resources in the country, Eskom (2012) and Nkhonjera (2017) contended that climate variabilities in the Waterberg and Highveld regions would intensify the demand for water from the Olifants and Mokolo catchments. This is likely to affect both water-dependent ecological activities and socio-economic sectors, predominantly energy and agriculture, in a negative manner.

CONCLUSION AND RECOMMENDATIONS

The present paper assessed the interactions between the elements of water, energy and climate change, the result of which is considered one of the emerging threats to the attainment of the country's energy and water security. The study shows that the intertwined relationship between the water, energy and climate change sectors in South Africa is inevitable, pointing to the existence of a WECC nexus. This is confirmed by the data used to assess several key interfaces between the sectors of WECC. Despite the paper attesting that data is paramount for the evaluation of nexus interlinkages, the study also revealed limitations in the existing systems and processes for measuring and availing data which links some of the WECC components in South Africa. The inadequacies in these systems are aggravated by the limited coordination and integration of approaches for the management of this nexus. Any gap in the data management system associated with the WECC nexus has the potential to derail the country's plans to manage this nexus effectively and in an integrated manner. South Africa should, therefore, move toward the improvement of management systems to ensure data is collected, stored, accessible, and used to inform the emergence of an institutional and policy framework for sustainable resource management.

While the nexus approach indicates that the water, energy and climate change sectors are equally important and should be managed as such, the current situation in the country presents South Africa with an opportunity to assess this nexus within the context of water resource management. This is key for the enhanced understanding and governance of the WECC nexus, largely due to the crosscutting role that water, despite its finite status, continues to play across various sectors in the country. This paper recommends that a water-centric approach be adopted to enhance the establishment of an evidence-based institutional and policy framework to respond to the socio-economic challenges associated with the WECC nexus.

DATA AVAILABILITY STATEMENT

The data was made available specifically for this project. Requests to access these datasets should be directed to SMM at steviemathetsa@gmail.com.

AUTHOR CONTRIBUTIONS

SMM collected the data and wrote the article in consultation with MDS and ITR who were the supervisors of the PhD research project. All authors contributed to the article and approved the submitted version.

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Appreciating the Resilience and Stability Found in Heterogeneity: A South African Perspective on Urban Household Food Security

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Urban food security has long been viewed as secondary to rural food security in Africa, and with the migration of large numbers of individuals from rural to urban settings, it has become crucial to place more focus on urban food security. More so, in Southern African peri-urban areas, where high unemployment rates amongst the youth exist. Often, the interventions toward reducing food insecurity in urban settings are taken from those previously designed for application in the rural context. In this study, we aimed to measure the status of food security and identify the factors driving and constraining household food security amongst peri-urban households in Tembisa, South Africa, with the purpose of gaining an in depth understanding of the drivers of urban food insecurity within peri-urban communities. In order to accomplish this, FANTA's Household Food Insecurity Access Scale (HFIAS), which measures levels of food security and the Household Dietary Diversity Scale (HDDS), which measures the level of nutritional intake of households was applied. Food prices of the formal and informal markets were monitored over a period of 6 months. A significant decline in household food access over a 4-year period (2013–2016) was observed in addition to low-quality diets. The most commonly used coping methods during periods of low income included borrowing either money or food from friends and neighbors, this was done in conjunction with various other coping strategies. Much of the declining food access was attributed to the inflation of food prices, the lack of employment, lack of formal employment and a high number of household members to breadwinner ratios. High reliance solely on financial capital remains a limitation to the livelihood of urban households. Informal markets are an imperative driver of food security in these peri-urban communities and provide improved food price stability, temporal, and geographical food access through less volatile food pricing, compared to formal markets. Furthermore, government initiatives such as social grants and school feeding schemes have proven to be critical in reducing the vulnerability to food insecurity of most households.

Keywords: food security, urban, rural, informal markets, formal markets, food price hikes, dietary diversity, food access

INTRODUCTION

With a commitment to achieving the Sustainable Development Goals (SDG), one must ask: "Is zero hunger achievable within the next decade?" Even more so in Africa, where food insecurity is undoubtedly a challenge and remains a hindrance to healthy and productive societies. Although some may look to Africa as the world's future breadbasket, more than 25% of the population is severely food insecure (United Nations Human Settlements Programme, 2018; FAO, IFAD, UNICEF, WFP, and WHO, 2021). There have been ample policy initiatives driving the food security conversation, however, these have often not considered what some refer to as the "looming urban food security crisis" or the "invisible crisis" (Crush and Frayne, 2010; United Nations Human Settlements Programme, 2018), commonly referred to as urban food security.

With Africa's population rapidly urbanizing at a faster rate than the rest of the world, even exceeding previous projections, urban food security will need to become an even more urgent priority when framing food security policy. Between 2015 and 2021, the urban population grew by more than 397 million people, with more than 90% of the growth coming from developing regions (Pörtner et al., 2022). The literature has highlighted that food security policies in Africa, are disproportionately biased toward rural dwellers (Battersby and Watson, 2018; Crush and Young, 2019; Berlie, 2020; Jonah and May, 2020; Moseley and Battersby, 2020). In light of the rural bias, food security is often addressed as a matter of availability rather than access. Thus, calls for increased agricultural productivity have been central to food security policy (Owoo, 2021). Unfortunately, urban households are often net consumers and rely heavily on the markets to access food. Several studies highlighting the prevalence and severity of food insecurity amongst urban households have been important in driving the increased interest in urban household food security. One such study showed that although many food-insecure households were observed amongst rural households, urban and peri-urban households experienced an increased severity of food insecurity. In 2012, Crush found that of the 11 Southern African cities represented in his study, eight cities had severe food insecurity levels of over 60% (Crush et al., 2012). To experience severe food insecurity an individual or household must have cut back on meal size or frequency often, and/or experiences any of the three most severe conditions (running out of food, going to bed hungry, or spending a whole day and night without eating) unwillingly, and over 60% of households in 8 Southern African cities had resorted to the above coping strategies (Coates et al., 2007 and Crush et al., 2012). Chileshe (2013) documented 90% of the households in Lusaka's informal areas were food insecure. Studies conducted in Addis Ababa, further highlight the prevalence of urban household food insecurity (74.9%), significantly exceeding national household food insecurity (35%) in Ethiopia (Birhane et al., 2014). In 2019, Stats SA reported that of the 1.6 million food-insecure households reported in South Africa, over 60% were in urban areas. The above stats do not only highlight the prevalence of food insecurity within urban Southern African communities but also emphasize the need for the development of policies that drive targeted solutions to address this "looming crisis". However, to develop these targeted policies, one must first understand the underlying issues driving food insecurity within urban and peri-urban communities, their associations and pathways.

Contrary to their rural counterparts, urban and peri-urban dwellers tend to have fewer diverse coping mechanisms. Where rural households make use of diverse streams of capital (social, natural, financial, and human) urban households tend to have limitations in accessing these due to cultural and/or changed social circumstances. The majority of vulnerable urban communities reside on the periphery of cities, with limited access to land and natural resources. Due to similar and limited livelihood strategies with neighbors, social capital can often be easily eroded or unavailable. South Africa's peri-urban areas, otherwise known as Townships, are marked by high levels of unemployment and poverty resulting from past inequalities. Townships are strategically placed on the outskirts of highly developed areas and were not designed to achieve maximum productivity and economic growth.

Informal markets are an imperative driver of food security in these peri-urban communities (De Zeeuw et al., 2011; Peyton et al., 2015). Unlike formal retail outlets, informal retail outlets tend to sell goods to the local community in smaller affordable volumes (Battersby and McLachlan, 2013; Peyton et al., 2015; Tacoli, 2016). Furthermore, informal shopping outlets are often spatially and temporally more accessible to peri-urban households. Markets such as spaza shops operate for longer hours than formal retailers, allow for credit purchases and usually have a comprehensive understanding of the needs of their community.

South African peri-urban and urban landscapes present an informative case to shed light on issues related to urban food security in Southern African cities. The peri-urban landscapes across the country continue to experience high numbers of rural-urban migration, resulting in a phenomenon referred to as the "urbanization of poverty" (Ravallion, 2009). The current South African urban population sits at 67.35% and is set to exceed 70% by 2025 (Crush and Frayne, 2011; United Nations, Department of Economic and Social Affairs, Population Division, 2019). South Africa is food secure at a national level; however, the country is food insecure at a household level (Statistics South Africa, 2019). In Gauteng, a highly urbanized province in South Africa, which hosts Africa's richest square mile, ∼18% of all households go hungry. Furthermore, in 2017, Stats SA reported the highest documented incidences of malnutrition in Gauteng and the second-highest number of households living in poverty in 2014 (Department of Agriculture Forestry Fisheries, 2014; Statistics South Africa, 2016). Urban household food security, though prevalent in Southern African communities, will not be efficiently addressed until we focus on the urban-specific associations and pathways of food insecurity (Jonah and May, 2020). Battersby and Watson (2018) further state that: "food security programming at the global, regional, and national scales continues to be based on a narrow conceptualization of food security that is poorly equipped to address the growing need for urban solutions". In light of this, this study aimed to measure the status of food security and identify the factors driving and constraining household food security amongst peri-urban households in Tembisa, South Africa. Although focused on South Africa, the analysis has implications for the rest of Southern Africa.

METHODOLOGY

Study Area

This study was conducted at Tembisa, situated in the Northeast of Ekurhuleni metropolitan municipality in the heartbeat of the Gauteng Province, South Africa (**Figure 1**). Ekurhuleni Metropolitan Municipality hosts a large proportion of seriously hungry urban households; however, at the time of the study, few studies had been conducted to analyze the state and drivers of food insecurity within Tembisa. With a population of over 512,000, Tembisa is the second most populous township in South Africa after Soweto (O'Neill, 2021). Established in 1957, the history of the township stems from the apartheid era when the forcible removal of black South African families from their homes was rife. In addition to existing pressures, Tembisa receives a large influx of the 10 000 new/additional migrants Johannesburg welcomes each month (Statistics South Africa, 2012; United Nations Human Settlements Programme, 2018). Although urban agriculture is often seen as a solution to food insecurity in the township, the soil fertility in Tembisa is low and the costs of inputs are high. A study on a place such as Tembisa presents an opportunity to gather more evidence to build a case for the understanding and prioritization of food security in peri-urban communities.

Data Collection

Temong, Teanong, and Ethafeni, three sub-areas of Tembisa township, were selected for this study. The selected sub-areas needed to be most representative of Tembisa in terms of the economy and educational levels. Selecting the three sub-areas was done in consultation with a representative/town planner from Ekurhuleni Metropolitan Municipality to avoid bias toward highly advantaged or disadvantaged sub-areas.

A semi-structured interview questionnaire was developed in line with the objective of the study, which was to identify the factors driving and constraining food security amongst peri-urban households in Tembisa. The questionnaire was made up of a combination of open and close-ended questions on socio-demographics, shopping practices, long-term food access, coping strategies in light of food shortages should they occur and spending habits. To determine the factors driving food insecurity, we first needed to understand the status of food security in the study area. The Household Food Security Index Access Scale (HFIAS) and the Household Dietary Diversity Scale (HDDS) Index developed by the Food and Nutrition Technical Assistance Program of USAID were used to assess household food security (**Appendix 1**; Swindale and Bilinsky, 2006; Coates et al., 2007).

In addition to considering changes in food security levels over time, the HFIAS enables one to note the different stages households experience before experiencing chronic food insecurity (Castell et al., 2015). This HFIAS is also a good measure of the levels of food security that different households may be experiencing at the same point in time, thus enabling the proper evaluation of the state of household food security. When compared with other tools (CSI, rCSI, FCS, and HHS) the HFIAS measured more food security-related factors such as stability, quality, quantity and acceptability of food consumed, whereas other tools only measured two of these factors, making the HFIAS a more suitable tool for this study (Maxwell et al., 2013). It was further established that the HFIAS is more informative when used in conjunction with other tools such as the HDDS (Maxwell et al., 2013). After consideration of the above, it was decided that the HFIAS and HDDS would be the most suitable tool for measuring food and nutrition security for this study.

A key component of this study involved understanding the role local markets, both formal and informal, played in urban household food security of the 140 households sampled in Tembisa. The four sampled supermarkets and shops were selected based on the dominance of household preferences, which were determined during the interviews. Additionally, desktop research was conducted to determine the relationship between household food security and economic factors. Food-stuff brands and quantities were determined with the help from a key informant from the study areas. The monitoring of the prices of these foodstuffs were guided by key informants and food price surveys conducted in South Africa, which made use of the similar products (Statistics South Africa, 2013). The price data were collected on a monthly basis from 3 of the most popular supermarkets in the area over a period of 6 months. The popularity of these supermarkets was determined during household interviews where each household was questioned where they shopped for food. In addition to the 3 supermarkets, 12 spaza shops (4 in each site) and one vegetable/fruit (street vendor) market with a series of stalls were used to monitor food prices. Both formal and informal markets were monitored in this study since most participants often made use of one or the other of these to source their food.

Interviews

In-person interviews were conducted between August 15 and September 30, 2016, with 140 willing participants over 18 years of age. To maintain anonymity, each participant was given a number that followed the first three letters that made up the name of their sub-area, e.g., the first participant from Teanong would be referred to as "TEA 1". Snowball sampling (where future interview participants are recruited from the acquaintances of those being currently interviewed) was used as method of securing interviews with Tembisa households. To further understand how and whether food access had changed in the previous 4 years, participants were asked to rate their access to food between 2013 (Past) and 2016 (Present), on a scale of one to three, with one being inadequate and three being adequate. As part of the survey, we asked about wage changes over the past year. This was done to identify any relationships between food security, wage changes, and purchasing power. Understanding that many households obtain food from local supermarkets and spaza shops, we devised an additional questionnaire for the shop owners and managers. This questionnaire aimed at identifying the drivers of food price hikes within their stores. Participants were asked to list coping strategies used to manage during periods of food shortages. The

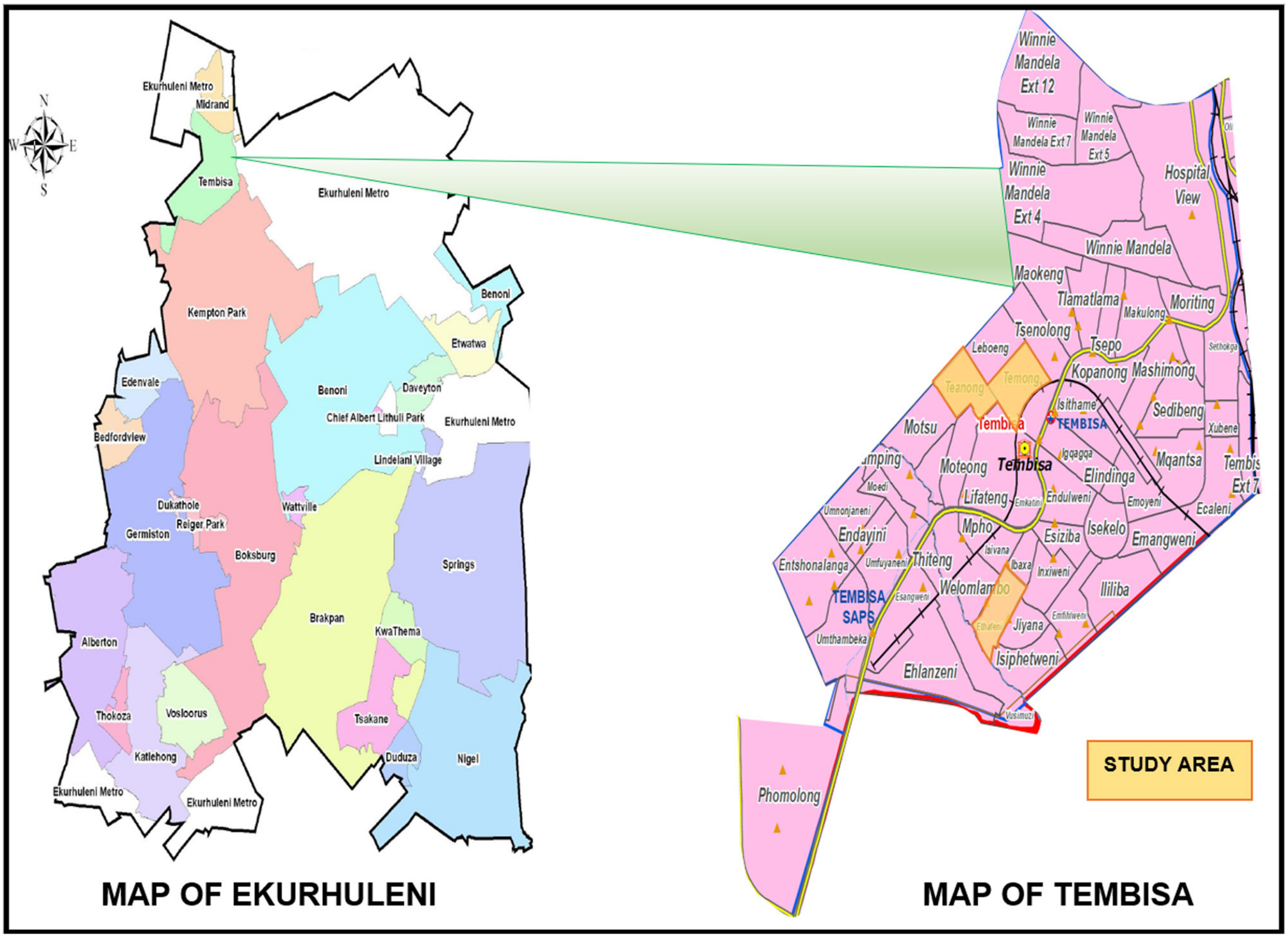

FIGURE 1 | The location of Tembisa situated in the East of Gauteng, in Ekurhuleni Metropolitan Municipality, indicated by the area shaded in red. With the study areas (Teanong, Temong, and Ethafeni) in Tembisa shaded in yellow.

four common strategies were selected to construct the conceptual framework for the study.

Data Analysis

The data were analyzed using Microsoft Excel 2013 and SPSS for Windows version 22 (SPSS Inc., Chicago, Illinois). Descriptive statistics, One-way Anova and Chi-squared tests were used for data analyses.

Using the occurrence of "yes" responses to the Household Food Insecurity Access Score questions, the HFIAS was determined. The following formula was used to determine the Household Dietary Diversity Score:

HDDS
(0–12)
Total number of food groups consumed by members of the household.
Values for A through L will either be "0" or "1".
Sum (A + B + C + D + E + F + G + H + I + J + K + L).

Making use of 12 food groups, the diversity of household food intake was determined. A score between 0 and 12 was used to determine household dietary diversity where a score of 12 would be the most diverse and 0 represent the lowest diversity. The average household Dietary Diversity Score was determined using the following formulae:

$$Average\ HDDS = \frac{Sum\ (HHDS)}{Total\ \#\ Households}$$

Descriptive statistics were adopted to determine overall household food security and dietary diversity. Statistical analysis on demographic data were calculated using the Chi-square tests.

Finally, Consumer Price Index (CPI) data were accessed from the Statistics South Africa database and used to map out the relationship between cumulative CPI change and food access between September 2013 and September 2016.

RESULTS

Household Food and Nutrition Security

The data on household food security shows that 76% of the 140 households interviewed were food insecure and of these 31% were severely food insecure. These levels of food security were often accompanied by households/individuals within households skipping meals and reducing nutrient intake. One participant over the age of 50 would simply drink water and go to sleep when he had no food available. An average household dietary diversity score of 4.35 was observed in the households that presented with moderate food insecurity. Half of the severely food insecure households had a dietary score that fell below 4, which is relatively low. A strong association between the HDDS household food security was observed [χ^2 (12, N = 140) = 26.594, $P < 0.01$]. A lady who sold[1] *spahlo/kota* for a living recalled eating the same meal throughout the week due to insufficient funds to afford a diverse diet. *Pap* with sour milk or cabbage were amongst foods considered to be default survival food. Another respondent stated that: "we eat to get full, not to enjoy." Cabbage was often referred to as "poor person's food." However, it was an ideal staple for households who could not afford anything else, as one head of cabbage could feed a family of 5 or more. Less than a quarter of the households recalled fruit intake in the past 24 h with one respondent saying: "I cannot buy fruit; they are not a priority, because you cannot feed the whole family with fruit." Whilst another participant implied that fruit were "rich people foods." Cereals, meat and vegetables, although not diverse, were the most commonly consumed foods.

Characteristics of Food Insecurity

A statistically significant association χ^2 (6, $N = 140$) = 13.135, $p < 0.05$ was observed between food security and the job sector. It was clear that a relationship exists between the job sector that the breadwinner works in and food security, however, this relationship was more visible at certain levels of food security (namely food secure and severely food insecure). Households with formally employed breadwinners had fewer cases of household food insecurity (**Table 1**). Severe cases of food insecurity were reported by more households with unemployed breadwinners and also households relying on informal income (**Table 1**).

There was some confusion between employment and unemployment, where most individuals who were earning a living from the informal sector would categorize themselves as "unemployed", this error was corrected for in the analyses through reclassification of data. Those previously classified as unemployed whilst working in the informal sector were re-classified under the same banner as the informally employed livelihoods. Before the re-classification, more than 50% of the households were classified as unemployed. After re-classification, only 12% of the households constituted of family heads which were unemployed. In total, 39% of the "employed" households worked in the informal sector and the remainder were formally employed. In South Africa, informal employment sector makes a significant contribution to the economy of the country.

Households where tenants were not renting had more severe cases of food insecurity than household where tenants were renting, when the data were further explored, we found a strong association between household size and renting vs. non-renting tenants χ^2 (6, N = 140) = 60.742, $p < 0.001$. On average, renting tenants tended to have fewer household members than non-renting tenants which may explain the higher prevalence of food insecurity amongst non-renting tenants. Older participants in the study (above 40 years) displayed a higher severity of food insecurity than the younger participants (**Table 1**). The results display an association between the age of the participants and food security χ^2 (9, N = 140) = 17.196, $p < 0.05$. Some households relied not only on income from a parent, but also from child grants and grandparent's pensions. Those receiving grants would be expected to have higher levels of food security because of the additional source of income. However, it is the households' receiving grants which experienced higher proportions of food insecurity and even more severe levels of food insecurity χ^2 (3, N = 140) = 4.321, $p > 0.05$ (**Table 1**).

Food Security and Market Access

Households were requested to rate their access to food and how it has changed in the past 4 years including the year of the study (2016). The 4-year history was selected because going beyond 4 years may lead to a less vivid recollection food access. The difference between the 4 years was most visible in those experiencing adequate and inadequate levels of food access (**Figure 2**). There were higher proportions of households with adequate access to food and lower proportions of households experiencing inadequate food access in the first year (2013). However, as the years progressed there was a visible change in those proportions (**Figure 2**). A number of respondents reported reduced food access over time and attributed this change to their lack of employment due to job losses as well as food price hikes which put strain on breadwinners and their ability to afford basic goods. It is important to note that during the time of the study, a drought ravaged the country resulting in food price hikes.

The difference in the proportions was most visible in the final year (2016), where there were more households experiencing severely inadequate food access [one-sample $t_{(3)} = 4.142$, $p = 0.0247$], than those experiencing adequate food access [one-sample $t_{(3)} = 5.760$, $p = 0.0106$] (**Figure 2**). We also noted that the change in the number of households stating they had "mildly adequate" food access remained relatively stable throughout the 4 years, when compared to the other states of food access (**Figure 2**).

Food prices at formal shopping/supermarkets were the most volatile compared to spaza shops, which had consistent prices until March. During March 2017 increases in food prices were observed throughout all spaza shops, and this was said to

[1]A meal which comprises of a quarter loaf of white bread, slap chips (oil-soaked deep-fried chips), polony and cheese–depending on how much money a customer is willing to spend—This food is frequently consumed within South African townships and peri-urban spaces.

TABLE 1 | Summary statistics of the relationship between household food security status (based on Household Food Insecurity Access Scale) and demographic data of the study population, using the Chi-square statistical test.

Demographic factors	Category	Level of food security				*p*-value
		Food secure 24% ($n = 33$)	Mildly FI 4% ($n = 5$)	Moderately FI 41% ($n = 58$)	Severely FI 31% ($n = 44$)	
Job sector	Formal	30.8	4.6	41.5	23.1	0.041
	Informal	20.7	3.4	44.8	31	
	Unemployed	5.9	0	29.4	64.7	
Gender	Male	28.1	4.7	35.9	31.3	0.519
	Female	19.7	2.6	46.1	31.6	
Rental status	Yes	32.7	1.8	38.2	27.3	0.209
	No	17.7	4.7	43.5	34.1	
Age	18–28	38.6	3.5	36.8	21.1	0.047
	29–39	14	4.6	48.8	32.6	
	40–49	7.1	7.1	42.9	42.9	
	50+	15.4	0	38.5	46.1	
Household size	1–3	27.9	3	41.2	27.9	0.707
	4–6	18.9	5.7	37.7	37.7	
	7+	21.1	0	52.6	26.3	
Government grant	Yes	16.9	3.1	41.5	38.5	0.236
	No	29.3	4	41.3	25.3	
Housing type	RDP	0	11.1	33.3	55.6	0.172
	Shack	0	0	75	25	
	Back room	35.4	2.1	37.5	25	
	House	20.3	3.8	43	32.9	
Duration of stay	1–5	28.6	0	42.8	28.6	0.574
	6–10	30.8	7.7	38.5	23	
	10+	20	4.7	41.2	34.1	
Number of breadwinners	1	22.1	3.2	42.1	32.6	0.632
	2	23.1	5.1	38.5	33.3	
	3	60	0	40	0	
	4+	0	0	100	0	
Total income spent on food	<Than a quarter	50	0	25	25	0.155
	A quarter	30.2	7.6	39.6	22.6	
	Half	11.8	2.9	52.9	32.4	
	>Than half	16.1	0	41.9	41.9	

be associated with the[2] budget-speech and annual changes in the food basket. Adequate access to food and South Africa's Consumer Price Index (CPI) showed a negative relationship for the 4 years (2013–2016). The CPI increased constantly over the years and as the CPI increased the number of households with adequate access to food had declined (**Figure 2**).

Food prices at formal retail outlets were the most volatile, on the other hand, prices at the spaza shops were the least volatile, with Ethafeni spaza shops experiencing the least food price volatility. Finding a trend in the changes of food prices in major retail outlets was difficult. There were no clear trends noted in the 6 months of the study. Prices in retail outlets would rise and fall randomly with no indication of why this may be.

Coping Strategies

Various coping strategies were adopted, where the most common strategies were borrowing money from close friends and family, skipping meals or reducing quality/portions of their food intake "persevering" and taking on[3] piece jobs. In terms of "persevering" a respondent stated: "*When something is not there, it is not there, you need to accept the situation for what it is*." Borrowing money from friends, neighbors, and colleagues was the most common strategy used by Tembisa residents. Almost half (42%) of the residents made use of this strategy, often coupling it with other

[2]Annual occurrence in South Africa at the end of February, where the finance minister announces changes in national budget including important tax announcement which have an important bearing on basic food basket pricing.

[3]Low paying *ad hoc* jobs.

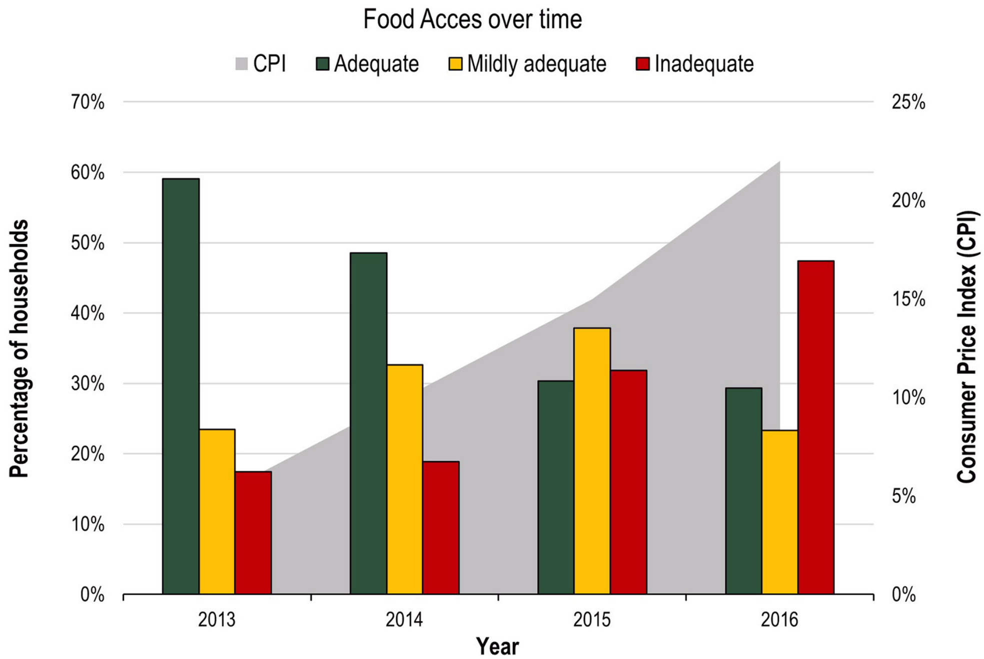

FIGURE 2 | The perceived state of household food access in respondent household, from 2013 to 2016 and the calculated cumulative national Consumer Price Index change across the same period–2013–2016 (CPI data retrieved from Stats SA database).

strategies, such as getting money from[4] *mashonisa* or "Other" unidentified methods Micro moneylenders in Tembisa, charge a 50% interest on whatever money they loan the residents, usually on a short-term basis. A respondent did however mention that when the *mashonisa* was your friend you could borrow money at a lower (30%) interest rate, which is still high.

DISCUSSION

The South African constitution clearly states that "everyone has the right to have access to sufficient food and water" 27 (1) (b). It further elaborates that "the state must take reasonable legislative and other measures, within its available resources, to achieve the progressive realization of each of these rights." 27 (2) (The Constitution of the Republic of South Africa, 1996). Three keywords and statements stand out in these sections, "everyone," "access," and "progressive realization of these rights." Historically, South African policy has always been concerned with food security, and regulations and measures have been put in place to ensure that it is addressed. However, food security in South Africa is still viewed as an issue of availability and not of access, thus undermining the needs of the urban poor. This is not unique to South Africa, Berlie (2020) notes that the urban poor in Ethiopia are often overlooked and undermined in research and government actions pertaining to food security. Dake (2021) highlights that even with increased reports of malnutrition in sub-Saharan Africa, urban food remains marginalized and largely ignored on the global food security and development agenda.

These flaws in food security policy are not those of legal framing. It is because of non-contextualized planning, that urban households continue to be undermined when addressing food security (Battersby et al., 2015). However, food security policy and planning will have to increase their focus on urban household food security as Africa's population continues to rapidly urbanize.

Drivers of Urban Food Security: Conceptual Framework

Food security is when all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their food preferences and dietary needs for an active and healthy life. Only 24% of the 140 households interviewed met this definition. Two factors set food-secure households apart from food-insecure households, formal employment and financial stability resulting in a spend of less than a quarter of their income on food. On the other hand, food price hikes, unemployment, informal employment, and the ratio of breadwinners to household members were the major factors contributing to urban household food insecurity (**Figure 3**).

In light of these drivers, borrowing money from friends and family was used as a coping strategy (**Figure 3**). However, this coping strategy became an indirect determinant of food insecurity because, although borrowing money eased hunger in the household in the short term, the long-term repercussions could not be overlooked. Due to similar financial restrictions among friends and family members, and the time frame

[4]Loan shark.

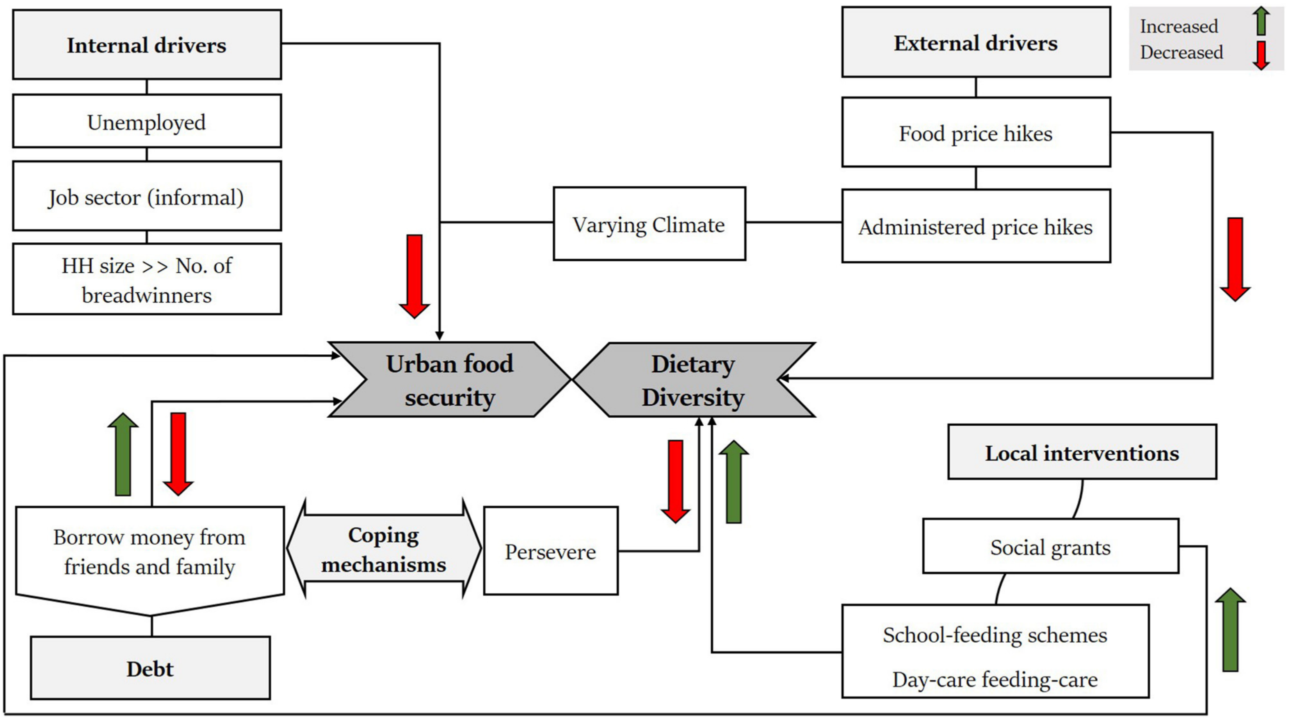

FIGURE 3 | This conceptual diagram illustrates the linkages between the drivers of urban food security and how they interact with each other in Tembisa.

in which one must return the funds, households often find themselves in similar situations where their relief is short-lived. Moreover, many of these households survived off piece jobs and *ad hoc* employment, where funds were sporadically available and could only take care of the household's present-day needs.

In addition to borrowing money, perseverance was used as a coping mechanism. This involved settling for lower quality diets and going hungry in the severest case (**Figure 3**). Similar strategies were observed amongst urban households in Kenya and Zambia during the global recession of 2008 and 2009 (Hossain et al., 2010). Unfortunately, this had the potential to negatively impact household food and nutrition security, with further impact on the health and vitality of individuals in the household and potential negative implications such as chronic malnutrition, child stunting and cognitive impacts on developing adolescents. These have cascading effects on learning abilities and can reduce the potential of affected individuals to thrive in the educational system.

Through access to social grants, several households received a monthly stipend (32–136$ monthly) that contributed to food security *via* child grants and older persons' grants (available to unemployed individuals 60 years and older). As expected, households relying on social grant stipends had a pre-disposition to severe food insecurity. Faber et al. (2017) report households receiving social grants were less likely to be food secure and had a low living standard. Nevertheless, these grants acted as a safety net and provided the household with access to markets, helping reduce the severity of food insecurity experienced by household members.

Another element enhancing food security was the school-feeding scheme offered through the National School Nutrition Program. The program provides two hot meals per day to primary and high school pupils situated in previously disadvantaged communities. The National School Nutrition Program is designed to enhance the pupils' active learning abilities, alleviate short-term hunger, and provide incentives to attend school. Beyond its intended role, the school feeding scheme was instrumental in shielding households from increased food demand during the school term. The absence of the program was even evident during weekends and even more so during school holidays. This is because vulnerable households would struggle to meet their food needs for up to 4 weeks.

Urban agriculture was singled out as a means of enhancing food security within vulnerable urban households, however, there has been limited evidence of its uptake within the studied community. There was only one occasion where a correspondent attributed her household's food security to a vegetable garden run by herself and a few volunteers at the local school. The gardens contribute not only to improved household food security but also to strengthening social cohesion. Urban landscapes and livelihood strategies often suffer from eroded social capital through decreased social cohesion, which negatively impacts the diversity of strategies available to urban households when in need (Harris et al., 2014). Several studies have suggested that urban gardens and agricultural projects indirectly play a role in strengthening social cohesion amongst urban communities (Harris et al., 2014; Veen et al., 2016; Tornaghi, 2017). Cilliers et al. (2020) further highlights the need for urban planners be more engaged with identification and utilization of urban agriculture as a form of social capital.

Surprisingly, participation in food gardening and urban agricultural initiatives did not resonate well amongst the study cohort. The limited uptake of urban agriculture may be attributed to the age of the participants interviewed, who were mainly 40 years old and younger. Thornton (2008) attributes the limited uptake and negative perception of subsistence farming by the youth to the legacy of apartheid and the homeland system. Whilst lack of capital, the uncertainty of farming, and lack of land are often blamed for the disinterest of youth in agriculture in other parts of Africa (Marson, 2022).

Higher food insecurity rates among homeowners compared to those who rent may be related to their responsibilities and commitments vs. those of tenants. According to Lucci et al. (2018), a lack of accounting for non-food items in urban households, such as housing and payment of other services, that consume a significant share of a homeowner's budget could result in the underestimation of household food insecurity. The additional strain on urban poor households' budgets is likely to increase levels of food insecurity as seen in this study.

Apart from the mortgage payment cost which often surpasses that of the household renting a backroom, those living in their own homes tended to have more household members than those living in back rooms, and therefore, more people to support. This may explain why homeowners—whether RDP or other housing—experienced higher levels of food insecurity. Furthermore, those living in rented out back rooms were mostly youth and young couples, often with fewer responsibilities and financial commitments.

Urban Agriculture

Agricultural programs play an integral role in achieving food security in peri-urban and urban communities and are often cited as the single most effective approach to addressing urban food security. However, to be successful in these already vulnerable landscapes, a lot more consideration needs to be taken into the implementation of urban agriculture-centered projects. Applying urban agricultural concepts in a landscape where the uptake of urban agriculture is already low, one must first address structural limitations. Many of these peri-urban settings are defined by limited spaces, deficient soils and inadequate access to water. Building innovative urban agriculture protocols is the first step. One such solution may be pushing for low irrigation crops, through dry farming—which although it produces a lower yield, can be adequate for subsistence farming. The feasibility of this is yet to be understood. This is because it may have to be applied through vertical farming, while dry farming usually makes use of the below-ground soil moisture. Exploiting coal fly ash as a soil ameliorator could be another way to address the soil moisture and nutrient content limitations.

An annual total of over 30 million tons of coal fly ash are disposed of, in South Africa (Eskom Holdings SOC, 2020). A variety of studies have examined the use of fly ash to modify soil characteristics, including its chemical, physical, and biological properties (Yunusa et al., 2012; Raj and Mohan, 2014). The ash can be used to improve soil texture, moisture retention and available nutrients (NPK) and has been reported to increase plant growth and crop yields (Yunusa et al., 2012; Raj and Mohan, 2014). The use of such innovations in combination with low-cost methods, such as mulching, could lead to improved urban gardening that requires a low financial input. More specifically, in areas characterized by nutrient-deficient soils. An adequate methodology would have to be developed to prevent phytotoxicity because of heavy metal uptake from the ash to the plant or crop (Gibczyńska et al., 2006). As increased temperatures have been projected for Southern Africa, further research on the performance of fly ash in changing temperatures is needed.

All urban agriculture planning should take futures thinking into consideration. The impact of climate change in cities, through increased drought stress and further exacerbation of this through the heat island effect, should remain central to the development of adequate urban agricultural programs, if they are to be sustainable (Pörtner et al., 2022).

The Informal Economy

Other results highlight the role of formal and informal markets in achieving food security amongst township and peri-urban households. In the current study, the food prices of informal markets were four times less volatile than the prices of formal markets. The combined use of these markets allows for ease of diversification when purchasing food, which is especially relevant where incoming finances are sporadic and inconsistent. Under these circumstances, bulk buying is not possible, and households tend to limit their food quantities based on daily purchases, present needs and available income from the day's earnings. This in itself creates a sense of security for low earning households who have to consider all their needs and have little room to make alternate decisions should food prices change. Thus, many peri-urban communities access food markets through informal markets. Chileshe (2013) found that 91% of peri-urban residence purchased their food from informal markets. Tawodzera and Zanamwe (2016) had similar observations in Harare, Zimbabwe.

Planning around peri-urban areas often revolves around development and ease of access to formal markets. Although critical in increasing job opportunities. The densely populated nature of peri-urban spaces means only a small proportion of households from the population benefit. In some cases, informal vendors are frowned upon or pushed out of the landscape to make way for commercial buildings and supermarkets (Battersby and Watson, 2018). In no way does the above suggest that peri-urban formal market penetration is not beneficial, but it highlights the importance of incorporating informal markets into urban planning strategies. The heterogeneity of formal and informal markets in a given area allows vulnerable households to obtain food with ease. To this point, Davies et al. (2020) highlights the need for urban planners to account for the manner in which urban poor navigate urban food systems in which informal trading, urban agriculture, traditional markets, and modern food retail all play a critical role.

Informal markets are not only key to providing food access, but also assisting in household food stability. Food "stability" is defined as the steadiness of factors that may have an impact on the availability, access and utilization of food, such as the state of climate change, food prices, politics and economic stability (Food Agriculture Organisation, 2008).

Unemployment Rate

If the 2008–2009 financial crisis, the 2015–2016 drought and COVID-19 have taught us anything, it is the need to build and enact robust and dynamic policies that are beneficial to all. These key periods were accompanied by increased job losses and food price hikes, the two most significant drivers of food insecurity in this study. During the recession, there were up to 800,000 job losses in South Africa alone (Verick, 2012). In Zambia and Kenya, the strain food price inflation placed on households was extreme, and still evident months later (Hossain et al., 2010). COVID alone not only recorded increased cases through job losses, but also loss of income through COVID-related deaths of breadwinners. With its economy having shrunk by an estimated 7%, Southern Africa was the hardest hit by COVID-19, out of the five African sub-regions (Anyanwu and Salami, 2021).

In 2021, South Africa's unemployment rate reached a record high of 35.3% (Statistics South Africa, 2022). These stats were worse amongst individuals without tertiary education and job losses were reported to disproportionately affect this group. Peri-urban landscapes are characterized by low education levels and bear the brunt and increased pressure of high unemployment rates. Several learnership opportunities offered to both matriculated and non-matriculated individuals are made available in South Africa. Many of these include a small stipend and a recognized certificate in the related skill, at the end of the program. These may provide the potential to upskill household members, with the co-benefit of increasing their employability. However, further insights into the drivers of decreased tertiary education in peri-urban areas are needed. These factors all have a bearing on food access and ultimately, food security.

CONCLUSION

At the start of this research, we set out to understand the key drivers of urban household food security in South Africa's peri-urban landscapes. In doing so, we discovered urban resilience and adaptability. Hossain et al. (2010) refers to it as the "undermined resilience". Unlike rural landscapes, that give way to multidimensional livelihood strategies, urban and peri-urban communities rely mainly on the use of one livelihood strategy—financial capital. And so, households in urban landscapes, learn to diversify their approaches to and uses of financial capital, in order to meet their daily needs. This phenomenon is observed throughout the continent. In as much as these strategies contribute to the wellbeing of urban households, many of these households still remain food insecure. How do we then leverage off our understanding of how urban and peri-urban communities operate to enhance the health and vitality of urban communities. More especially in a region, which is urbanizing at a faster rate than any other region in the world?

Studies of this nature should act as a baseline for planning mitigation and adaptation strategies for countries that are soon to have higher urban populations. Especially where migration to urban settings involves, not only the migration of wealth, but also of vulnerability and poverty into areas already experiencing increasing negative pressures of poverty.

In as much as urban agriculture shows positive impacts in improving household food security, further action is required to build robust, innovative systems to ensure the success of these programs. The cost of participating in these programs should be relatively low and not limited to available land. Furthermore, as the climate becomes increasingly warmer, these strategies will need to incorporate futures thinking in order for them to remain sustainable and feasible under the projected change in climate.

We note that the role of the spaza shop owners, street vendors and informal markets as a whole should not be undermined in such studies, as these stakeholders understand the needs and behaviors of the communities addressed in studies of this nature. Furthermore, the input of informal vendors may prove to be of importance in timely collection of data for the purpose of building sustainable solutions and urban food security policies. We need to enable and facilitate greater partnership between informal players and city planners. It is important to build off community strengths, one such strength being the informal market, which acts as a safety net and is a driver of geographical, temporal and financial food access and stability.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by University of the Witwatersrand Ethics Committee. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

Research conceptualization, methodology, formal analysis, funding acquisition, and original draft preparation was done by RN. The editing and supervision were conducted by MS. Both authors have read and agreed to the published version of the manuscript.

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SUPPLEMENTARY MATERIAL

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Retraction: The effect of productive safety net programme on household food consumption and dietary diversity in Ethiopia

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Greenhouse gas emissions in irrigated paddy rice as influenced by crop management practices and nitrogen fertilization rates in eastern Tanzania

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In rice production greenhouse gas emission (GHG) reduction is an important task for many countries, Tanzania included. Of global agricultural GHG emitted from rice fields, about 30 and 11% are represented by CH_4 and N_2O, respectively. For successful climate smart rice cultivation, rice management practices, including nitrogen fertilization are two key crucial components that need evaluation. The objective of this study was to evaluate the crop management practices and N fertilization on yield and greenhouse gases emission in paddy rice production, Experiments were designed in split-plot randomized complete block and replicated three times. Two rice management practices namely conventional practice (CP) and system of rice intensification (SRI) and six rates of nitrogen fertilizer (absolute control, 0, 60, 90,120 and 150 kg N ha^{-1}) were applied in two consecutive seasons. The Source-selective and Emission-adjusted GHG CalculaTOR for Cropland (SECTOR) was used to calculate the GHG emission. Methane emission was in the range of 88.7–220.6 kg ha^{-1}season^{-1}, where higher emission was recorded in CP treatments (ABC, CP 0 and CP 120N) compared to SRI treatments. SRI reduced methane and carbon dioxide emission by 59.8% and 20.1% over CP, respectively. Seasonal nitrous oxide emissions was in the range of no detected amount to 0.0002 kgN_2O ha^{-1} where SRI treatments recorded up to 0.0002 kgN_2O ha^{-1} emissions while in CP treatment no amount of N_2O was detected. The interaction of system of rice intensification and 90 kg N ha^{-1} (SRI90N) treatment recorded higher grains yield (8.1, 7.7 t ha^{-1}) with low seasonal global warming potential (GWP) (3,478 and 3,517 kg CO_2e ha^{-1}) and low greenhouse gas intensity (0.42, 0.45 kg CO_2e per kg paddy) compared to other treatments in wet and dry season, respectively. Therefore, SRI with 90 kg N was the treatment with mitigation potential and reduced GWP without compromising rice yield.

KEYWORDS

greenhouse gas emission, system of rice intensification, management practices, climate change, global warming potential, conventional practice, rice

Introduction

Global rice production is facing greatest challenge to meet an expected 34% increase in the world population by 2050 (Tilman et al., 2011; Alexandratos and Bruinsma, 2012; Tesfaye et al., 2021). Projected increases in the demand for rice will lead to increased application of fertilizers, particularly nitrogen-containing fertilizers and this will lead to increased greenhouse gas (GHG) emissions (van Beek et al., 2010; Van Groenigen et al., 2013; Arunrat et al., 2018).

Agriculture is the second major sector contributing to 24% of the global emissions next to the energy sector which contributes to 35% of GHG emission (Adounkpe et al., 2021; IPCC, 2014a). Agriculture contributes 14% of anthropogenic GHG emissions in the form of methane and nitrous oxide globally (IPCC, 2014a). At the same time agriculture can contribute to reduced net emission through bio-energy production and carbon sequestration. In Africa, between 1994 and 2014, the GHG emissions from agriculture increased at an average annual rate of between 2.9 and 3.1% (Tongwane and Moeletsi, 2018).

Paddy rice cultivation is one of the most important sources of anthropogenic emissions of greenhouse gases (GHGs), mainly nitrous oxide (N_2O), methane (CH_4), and carbon dioxide (CO_2) (IPCC, 2014a; Arunrat et al., 2018) and is the major driving force for climate change (Smith et al., 2014). Rice (*Oryza sativa L.)* cultivation rank the second after enteric fermentation and is the leading agricultural sources of CH_4, accounting for 22% of global anthropogenic agricultural emissions (Smartt et al., 2016). Paddy rice contributes 9–11% of the agricultural GHG emissions (IPCC, 2014a). Methane accounts for about 30% of the total global anthropogenic emissions (Gupta et al., 2021; Saunois et al., 2020). Eleven percent of global agricultural nitrous oxide (N_2O) emissions come from rice fields (IPCC, 2007; Win et al., 2020; Zhang et al., 2021). Rice is the single crop grown under continuous flooded-soil conditions which contribute to the formation of the anoxic environment, this leads to the production and emission of CH_4 (Smartt et al., 2016). CH_4 and N_2O are two major GHGs with a global warming potential (GWP) of 28 and 265 times that of CO_2 in a 100-year time horizon, respectively (IPCC, 2014b). Global warming potential from rice cultivation has been reported to be 2.7 and 5.7 times greater than that of maize (Zea mays L.) and wheat (Triticum aestivum L.) systems, respectively, with CH_4 specifically contributing more than 90% to the GWP of rice systems (Linquist et al., 2012).

Rice cultivation stimulates greenhouse gas (GHG) emissions from the soil into the atmosphere due to crop management practices such as irrigation water management, crop variety selection and fertilizer management, which in turn influences the biogeochemical processes of carbon and nitrogen in the soil (Islam et al., 2020). Methane is an end product of organic matter decomposition under anaerobic soil conditions (Linquist et al., 2012).Methane is produced by methanogens during organic matter decomposition, under an environment where the oxygen (O_2) and sulfate ($SO4^{2-}$) are scarce and nitrous oxide is produced microbiologically during the an aerobic conditions of paddy soils (Bajgai et al., 2019). Large proportion of CH_4 released from rice fields occurs through different ways such as aerenchyma tissues of rice plants, this transport mechanism contribute for about 90% of emissions, compared to 8.2% of emissions from ebullition and diffusion through the floodwater, respectively (Smartt et al., 2016).

Conventional practice (CP) coupled with continuous flooding irrigation and fertilizer application regimes, which is a common practice in Tanzania produces a huge amount of CH_4 (Katambara et al., 2013; Boateng et al., 2019; Islam et al., 2020). This practice makes the soil environment anaerobic, by decreasing the redox potential ($<$-150 mV) there by results in the anaerobic degradation of complex organic substrates by methanogens and the production of CH_4 (Islam et al., 2020). Various strategies for mitigating CH_4 emission from rice cultivation include water management practices, particularly promoting intermittent drainage and alternate wetting and drying (AWD) (Minamikawa and Yagi, 2009), system of rice intensification (SRI) (Gathorne et al., 2013); improving organic management by composting; using rice cultivars with few unproductive tillers, high root oxidative activity and high harvest index (Zheng et al., 2014); application of fermented manure like biogas slurry (Petersen, 2018) and adopting direct-seeding of rice (DSR) (Susilawati et al., 2019). Methane emissions differ across agro climate (rice growing seasons), soil types, locations (due to difference in organic carbon) (Gaihre et al., 2011; Datta et al., 2013; Sun et al., 2013).

Previous studies have shown that effective fertilizer and water management practices under system of rice intensification coupled with alternate wetting and drying irrigation could reduce GHG emissions by 40% (Ku et al., 2017; Li et al., 2018; Islam et al., 2020; Ramesh and Rathika, 2020; Sander et al., 2020; Win et al., 2020). Alternate wetting and drying irrigation greatly enhances the diffusion of atmospheric oxygen (O_2) into the soil, thus reducing the emission of CH_4 (Yang et al., 2012; Xu et al., 2015; Islam et al., 2020). Slight increase N_2O emission in AWD irrigation has been reported by Islam et al. (2020), Ku et al. (2017), Li et al. (2018) due to the increased nitrification of NH_4+ during the dry episode and the subsequent denitrification of NO_3- during re-wetting of dry soils, but it still reduces total GHG emissions from rice fields mainly due to reduced CH_4 emissions. Reducing the emission of CH_4 from the soil is the most effective way to mitigate the global warming potential in rice cultivation (Sander et al., 2014; Janz et al., 2019).

Mineral nitrogen fertilizer is very important and highest input in croplands, making almost half of global nitrogen input (Liu et al., 2010). Mineral nitrogen use is more widespread in West Africa compared with East and Southern Africa, which are the two major rice-producing regions in SSA (Tsujimoto et al., 2019). Surveys conducted on large-scale irrigation schemes, reported significantly low N application rates in Uganda (∼2 kg ha^{-1}), Mozambique (13–23 kg ha^{-1}), and Tanzania (15–22 kg ha^{-1}) compared to the rates in Burkina Faso, Mali, Niger, and Senegal (>100 kg ha^{-1}) (Nakano et al., 2011; Nakano and Kajisa, 2013). Nhamo et al. (2014) also reported that fertilizer application rates were commonly 5–20 kg ha^{-1} for lowland rice production in East and Southern Africa. In 11 countries of west Africa a cross-sectional survey of 1,368 rice fields reported that mineral N fertilizer was used in 81% of irrigated lowland fields (with average application: 100 kg ha^{-1}), 56% of rainfed lowland fields (65 kg ha^{-1}), and 38% of rainfed upland fields (37 kg ha^{-1}) (Niang et al., 2017). The average N application rate for the irrigated lowland fields in this survey is comparable with the average value for countries in Southeast Asia (FAO, 2002). Other studies have also reported relatively high N application rates in irrigated lowland fields in West Africa, for example, in a range of 72–112 kg ha^{-1} in Benin (Tanaka et al., 2013), 134–139 kg ha^{-1} in the Senegal River Valley (Tanaka et al., 2015), 37–251 kg N ha^{-1} in Mauritania (Haefele et al., 2001), and 73–147 kg ha^{-1} in Burkina Faso, Mali, and Senegal (Wopereis et al., 1999). The yield gap analysis verified equal or slightly greater yield potential and greater yield gaps of irrigated rice production, that is, large opportunities of yield increases with fertilizer inputs still remain in both Madagascar and Tanzania than most areas in West Africa (van Oort et al., 2015; Tanaka et al., 2017).

Though, only a portion of applied reactive nitrogen (N) is converted into food, the remaining is lost through various pathways like, denitrification, nitrate leaching and ammonia volatilization (Cassman et al., 2002; Tilman et al., 2002; Tesfaye et al., 2021).Various studies have reported that nitrous oxide (N_2O) emissions are associated with nitrogen (N) fertilizer application and dry land conditions (Arunrat et al., 2018) while flooded fields are a significant source of methane (CH_4) and contribute little to N_2O emissions (Shang et al., 2011; Wang et al., 2011; Yao et al., 2012).

During the Paris Climate Agreement of 2015, countries agreed to limit global temperature increase to below 1.5°C by reducing GHG emissions and are responsible to report their nationally determined contributions (NDCs) (UNFCCC, 2015; Gyanchandani, 2016; Elkahwagy et al., 2017). Like other countries in the world, Tanzania is looking for the best GHG mitigation options across all sectors, including paddy rice cultivation in agriculture sector. Although the Tanzanian Government is committed to (UNFCCC) and desires to minimize GHG emissions while promoting irrigated rice production, data on GHG emissions continue to be a challenge although this information is required in the Nationally Determined Contributions (NDCs) and climate change mitigation options. Indeed, the measurement lapse is a challenge to many developing countries especially in Africa (Nyamadzawo et al., 2013; Rosenstock et al., 2016; Boateng et al., 2017; Pelster et al., 2017; Zheng et al., 2019; Bigaignon et al., 2020). Current understanding of GHG emissions in sub Saharan Africa (SSA) is particularly limited when compared to the potential of the continent (Nyamadzawo et al., 2013; Kim et al., 2015; Boateng et al., 2017, 2020; Tongwane and Moeletsi, 2018; Bigaignon et al., 2020; Owino et al., 2020). This indicates that more research is thus needed in this regard to investigate the effects of crop management practices and nitrogen fertilization levels on greenhouse gas emissions from rice field. In line with this, it is hypothesized that the combination of system of rice intensification and optimum nitrogen would reduce greenhouse gas emissions and improve rice yield in irrigated lowland rice. To test this hypothesis, a study was conducted to evaluate the crop management practices and N fertilization on yield and greenhouse gases emission in paddy rice production.

Materials and methods

Experimental site and weather conditions

The field experiments were conducted at Mkindo farmer managed irrigation scheme located in Mkindo village in Hembeti Ward, Mvomero District, Morogoro Region, Eastern Tanzania. The district is located between latitude 6°16' and 6°18'South, and longitude 37°32' and 37°36' East and its altitude ranges between 345 to 365 m amsl. The experimental site located at latitude 6°15'13" south and longitude 37°32'19". Mkindo farmer managed irrigation scheme is about 85 km from Morogoro municipality (Gowele et al., 2020). The scheme was constructed in the period between 1980 and 1983. The scheme started producing rice in 1985 with only 17 ha under cultivation.

TABLE 1 Average temperature and rainfall of Mkindo Climatic conditions 1999-2020.

Month	Maximum temperature (oC)	Minimum temperature (oC)	Rainfall (mm)
January	33.7	20.2	106.9
February	35.0	20.0	83.2
March	32.8	20.3	208.2
April	30.6	19.9	250.3
May	29.2	18.6	112.6
June	28.5	16.6	25.4
July	28.7	15.6	9.9
August	29.3	16.3	18.0
September	30.8	16.8	19.9
October	32.2	18.9	52.6
November	32.2	19.4	85.9
December	33.7	19.8	116

TABLE 2 Selected soil physical chemical properties.

Parameter	Method of analysis	References
pH	Soil: water suspension (1:2.5) using glass electrode pH meter	(Mclean, 1982)
Organic carbon	Wet oxidation by Black and Walkley method	(Nelson, 1982)
Total nitrogen	Micro-Kjeldahl wet digestion-distillation method	(Bremner and Mulvaney, 1982)
Available P	Bray 1 method following color development using molybdenum blue method	(Bray and Kurtz, 1945)
Cation exchange capacity (CEC)	Neutral ammonium acetate saturation method (NH4-Ac, pH 7.0) followed by Kjeldahl distillation.	(Chapman, 1982)
Exchangeable bases (K^+, Mg^{2+}, Ca^{2+} and Na^+)	1N NH4-Ac (pH 7.0) method Mg and Ca was read by UV-VIS Spectrophotometer and K and Na Flame Photometer	(Chapman, 1982)
Extractable micronutrients (Fe, Cu, Zn and Mn)	DTPA extraction and determined by atomic absorption spectroscopy (AAS)	(Lindsay and Norvell, 1982)

Rice is the only crop produced in the scheme which serves as food and income generation. The scheme has arable area of 740 ha, with only 300 ha under rice cultivation and a near future expansion of about 620 ha is expected. The climate is tropical with two distinct seasons, dry and wet seasons. The average monthly maximum temperature at the experimental site ranges between 35.1 to 28.5°C for February and June while the average monthly minimum temperature ranges between 20.4 to 15.8°C for January, March and July, respectively. The average temperature and rainfall of Mkindo Climatic conditions for 21 years (1999–2020) has been reported in Table 1.

TABLE 3 Selected soil chemical properties of Mkindo Irrigation scheme at 0–20 cm of soil used in the study.

Soil property	Unit	Mean value
Soil pH (1:2.5)		5.36
EC	dS/m	0.03
Cu	mg/kg	3.47
Zn	mg/kg	2.6
Mn	mg/kg	7.13
Fe	mg/kg	1.65
TN	(%)	0.11
OC	(%)	0.59
OM	(%)	1.02
Av P	mg/kg	7.71
SO_4^{2+}-S	mg/kg	1.04
Exchangeable bases $Cmolkg^{-1}$		
Ca^{2+}		6.37
Mg^{2+}		1.51
Na^+		0.06
K^+		0.07
CEC		11

OC, organic carbon; TN, total nitrogen; TP, total phosphorus; Av P, available phosphorus; CEC, Cation Exchange Capacity; EC, Electric conductivity, OM, organic matter.

Soil sample processing and laboratory analytical procedures

Portions of the soil samples were dried, ground and sieved through a 2 mm sieve for physico-chemical characterization. Parameters measured were soil pH, particle size distribution, organic carbon and extractable phosphorus (AvP). Other parameters included total nitrogen, basic cations such as calcium(Ca), magnesium, potassium and sodium and micronutrients namely zinc (Zn), copper (Cu), manganese (Mn) and iron (Fe). Cation exchange capacity (CEC) and electrical conductivity (EC) were also determined for all the samples and the analysis followed the standard procedures as shown in Table 2 and results are shown in Table 3.

Experimental design and treatment details

Each season, the experiment was arranged in a split-plot randomized complete block design in triplicate with two factors (crop management practices in main plots and nitrogen

TABLE 4 Treatments applied in the study.

Main plot (Crop management practices)	Subplot (Nitrogen rates kg N ha^{-1})	Treatments combination
System of rice intensification (SRI-AWD)	ABC	SRI-ABC
	0	SRI-0N
	60	SRI-60N
	90	SRI-90N
	120	SRI-120N
	150	SRI-150N
Conventional (CP-CF)	ABC	CP-ABC
	0	CP-0N
	60	CP-60N
	90	CP-90N
	120	CP-120N
	150	CP-150N

Whereas ABC, Absolute control; SRI, System of rice intensification; AWD, Alternate wetting and drying; CP, Conventional practices; CF, Continuous flooding.

TABLE 5 Crop management practices.

Management practices	System of rice intensification (SRI)	Conventional practice (CP)
Age of seedling at transplanting	15 day	26 days
No. of seedlings/hill	1	3
Spacing (cm)	25 × 25	20 × 20
Plant population (m^{-2})	256 (16)	400 (25)
Water management	Alternate wetting and drying followed by drainage 10 days before harvesting	Continuous flooding followed by drainage 10 days before harvesting
Fertilization (kg ha^{-1})	Phosphorus and potassium 60 kg ha^{-1} and nitrogen had five levels 0, 60, 90,120,150	Phosphorus and potassium 60 kg ha^{-1} and nitrogen had five levels 0, 60, 90, 120, 150
Weeding (3 times)	Mechanical weeding by using cono weeders	Hand weeding

rates in sub-plots). The main plot was then divided into six subplots of size 16 m^2 plots were surrounded by consolidated bunds, and a 2 m buffer strips were left between main plots and 1 m for sub plots to provide access pathways and more importantly to minimize lateral movement of irrigation water and fertilizers between plots. The treatment details are shown in Table 4. Fertilizer treatments comprised six nitrogen rates; these include absolute control treatment (ABC) which did not receive any kind of fertilizer. The absolute control treatment intended to evaluate rice response under natural soil fertility. The N fertilizer treatments included a control treatment (N0) without any nitrogen fertilizer application but received P and K fertilizers, this treatment is required to assess crop response to nitrogen fertilizer application and to calculate fertilizer use efficiency. The amount of 120 kg N ha^{-1}, represents the current blanket recommendation for rice grown in Mkindo. The nitrogen fertilizer source was Urea (CON_2H_4, total nitrogen 46% N) and was applied in two splits, that is half 2 weeks after transplanting and the rest half at 55 days. Sources of full dose of phosphorus 60 kg ha^{-1} was triple super phosphate (45% P_2O_5) and potassium 60 kg ha^{-1} from muriate of potash (60% K_2O). Phosphorus and potassium fertilizers were applied at same rate to all plots during transplanting.

Crop management practices

A common variety TXD 305 was used. The trial rice variety takes 120–130 days to maturity under rainfed or irrigated ecologies. In establishing system of rice intensification SRI crop management practice plots, during transplanting a square grid pattern was created on the soil's surface using a wooden marker that demarcated distances of 25 × 25 cm between perpendicular lines. A 10-days-old seedlings were uprooted from nursery and transplanted one seedling per hill within 30 min of uprooting in both seasons. During weeding rotary (cono-weeder) and hand were used. Based on results in an earlier studies with the same rice variety under same area (Mkindo Irrigation scheme condition) conducted by Kahimba et al. (2013), Reuben et al. (2016) we decided to adopt the SRI recommended principles of spacing, seedling age, weeding and irrigation interval. In conventional practice (CP) crop management a 25-days-old seedlings were transplanted in puddled field at 20 × 20 cm spacing keeping three seedlings $hill^{-1}$, hand weeding was used in weed management as shown in Table 5.

Irrigation management

Application of continuous flooding irrigation was based mainly on local farmers' practice in CP plots. For the first 14 days after transplanting, a 3–5 cm water depth was maintained under both irrigation regimes to facilitate seedling recovery. Thereafter, SRI and CP plots were managed differently. Plots under CP were continuously flooded with a 3–10 cm water level until 10 days before harvest. After the first 14 days of transplanting the SRI plots were kept with a layer of 2 cm of water until 14 days after panicle initiation stage, and during the rest of the growing cycle, plots were maintained without standing water for 3–5 days before re-irrigation. Thereafter, the SRI plots were re-irrigated to 2 cm when water depth dropped to 15 cm below the soil; this took 2–3 days interval (Kahimba et al., 2013).The soil water

TABLE 6 Overview of specific Tier 2 requirements for GHG calculations in cropland within mitigation projects and approach in SECTOR.

Specific requirement	Description	Approach implemented in sector
Emission factors (EFs)	Free choice of EFs from IPCC and other sources	Emission library that can easily be expanded by location-specific EFs
Activity data	Rapid transfer of activity data from statistics or rapid transfer of activity data from statistics or survey data for large number of patches. Entry of activity data with frequencies (percentages) of water management practices	Entry format allows "copy-paste" of area, yield and fertilizer data for up to 100 patches
Aggregation	Aggregation for multiple seasons and scenarios	Aggregation framework with triangulation of GHG data (patch/season/scenario)
Scenario setting	Accounting for efficiencies in adoption of mitigation options	New coefficients for fertilizer-use efficiency as well as biophysical and economic barriers to adopting mitigation options

Source; Wassmann et al. (2019).

depths were measured and monitored in each SRI plot using PVC pipe installed in the plots at a 15 cm depths as described by Lampayan et al. (2015).The water depth was measured at 8:00 am and 14:00 pm each day using a 101 p7 flat tape water level meter (Solinst Canada Ltd., Geogetown, Ontario Canada). PVC pipes installed in SRI plots, with perforated holes with a diameter of about 0.5 cm each and spaced about 2 cm away from one another. The tube was buried vertically 15 cm into the soil and half of its length protruding above the soil surface. Pipes were installed near to the bund for easy water monitoring. After burying the PVC pipes the soil inside the tubes was removed so as bottom level is visible. After tube installation the water level inside the tube was checked and was the same the outside. Each of the main plots was irrigated separately. Irrigation water was provided from an irrigation canal and measured by a plastic ruler inserted into the plot.

Assessment of grain yield and yield components

At physiological maturity, grain yields were determined from a $(2 \times 2\,m) = 4\ m^2$ crop cut at the center of each field leaving a border rows. The rice plants in each plot were manually harvested and threshed separately. The harvested samples were threshed, cleaned, and sun dried for 2–3 days to a constant weight to obtain their dry weight. The moisture content of the dried grains was measured using a grain moisture meter (8988N Xiamen Hyhoo Imp. & Exp. Co., Ltd., Fujian, China). Finally rice grain yields were calculated based on standard moisture (14%) for rice storage.

Calculation of greenhouse gas emission

Intergovernmental Panel on Climate Change (IPCC) guidelines are applied through GHG calculators during assessment of GHG at national and subnational levels. Such calculators include SECTOR tool (Wassmann et al., 2019; Lai et al., 2021), EXACT tool (Grewer et al., 2013, 2016, 2018), the Cool Farm Tool (Hillier et al., 2011, 2013; Vetter et al., 2018).

In this study Source-selective and Emission-adjusted greenhouse gas CalculaTOR for Cropland (SECTOR) was used to calculate the emission of greenhouse gases. SECTOR is a greenhouse gas (GHG) calculator for cropland based on the values calculated from Intergovernmental Panel on Climate Change (IPCC) Tier 2 approach approved methodology (I. P. O., 2006) and (IPCC, 2019) refinement (Wassmann et al., 2019). SECTOR is guided by Tier 2 requirements and approach as shown in Table 6. This tool was developed by the International Rice Research Institute's (IRRI) GHG Mitigation in Rice Platform. Presently this tool is available in excel and requires inputs from the user on cropping area, yield, and management practices. SECTOR has been developed in response to increasing interest in mitigation studies in cropland, in particular rice production. These include the farm-diary data (Tables 7, 8) recorded such as:

a) Pre-season water management (number of days of flooding prior to crop establishment).
b) Number of days of crop growth (starting at transplanting stage).
c) Number and duration of drying events (the number of times when the water depth falls at least 10 cm below the soil surface; or the number of times in which the soil dries to the point of light cracking).
d) Total nitrogen input.
e) Water management before and during the growing season.
f) Residuals management.

The tool offers a high range of flexibility in terms of sourcing emission and activity data as well as selecting a range of scales for aggregation. Moreover, SECTOR provides a streamlined framework for accelerated data input that will facilitate rapid assessments of multiple scenarios for domains with many spatial units. Also SECTOR can easily be adjusted to incorporate new emission factors and calculation procedures expected in forthcoming revisions of the IPCC Guidelines. This tool is available as an XLS file and can be downloaded

TABLE 7 IPCC input parameters and value fed in SECTOR tool.

Parameters	Description	value
Equivalent value of GHG		
Carbon dioxide equivalent of methane (CH_4)	Carbon dioxide equivalent of CH_4—IPCC 2014	28
Carbon dioxide equivalent of nitrous oxide (N_2O)	Carbon dioxide equivalent of N_2O—IPCC 2014	265
Emission factor (EF) for CH_4	Lower range of global default EF for rice	0.8
Emission factor for fuel	Not considered	0
Singular N_2O emission factor	No adjustment	0
Pre-season water management		2.41,1
	For continuous flooding treatments; flooded > 30 days before season	
	For alternate wetting and drying treatments, non-flooded <180 days before season	
Organic amendment	Residual incorporated long (>30 days) before	0.19
Residual incorporation (from previous season)	Not considered (0%)	0
Within season management		
Direct emission factors of N_2O	Flooded soils: 0.47% of N as N_2O and non-flooded soil: 0.157% of N as N_2O	0.0047, 0.00157
In direct emission factor for N_2O	Not considered	0
Emission factor of fertilizer product	Not considered	0
Water management	Irrigated-multiple aeration, irrigated -continuously flooded	0.55, 1
Nitrogen fertilizer use	Total amount of nitrogen fertilizer (kg ha-1)	60, 90, 120,150
End season management		
Residue management	Not considered	0

jointly with its manual from http://climatechange.irri.org/SECTOR.

Estimation of global warming potentials and greenhouse gas intensity

In this study IPCC factors were used to calculate the combined GWP for 100 years [GWP = ($CH_4\,x\,25 + N_2O\,x\,298$), kg CO_2^{-1}] equivalents ha^{-1} from methane and nitrous oxide.

The Greenhouse gas intensity (GHGI) was calculated by dividing global warming potential (GWP) by grain yield (Ali et al., 2019).

Statistical analysis

Analysis of variance was performed on yield for all treatments over the total growth period of both seasons using the Genstart software 14th version. Global warming potential (GWP) of CH4 and N_2O was calculated in mass of CO_2 equivalent (kg CO_2 eq ha^{-1}) over 100-yr time horizon. A radiative forcing potential relative to CO_2 of 25 for CH_4 and 298 for N_2O (Myhre et al., 2013; Ali et al., 2019) was used. Anova tables are presented in Supplementary materials. Greenhouse gas intensity/yield-scaled global warming potential (GHGI/GWPY) was calculated by taking the ratio of GWP and corresponding grain yield for each treatment. These results were generated direct from the SECTOR calculator.

Results and discussion

Effect of crop management practices and nitrogen rates in methane emission

Methane emission in this study was in the range of 88.7–220.6 kg ha^{-1} season^{-1}, where higher emission recorded in conventional treatments (CP -ABC, CP- 0N and CP- 120 N) (Table 9). SRI reduced methane emission by 59.8% over CP. Relatively low amount of CH_4 emission from SRI treatments was due to partially aerobic soil conditions because of alternate wetting and drying water management cycles employed during experiment. Alternate wetting and drying irrigation water management under SRI greatly enhances the diffusion of atmospheric oxygen (O_2) into the soil, thus reducing the activity of CH_4 producing bacteria (Yang et al., 2012; Xu et al., 2015; Islam et al., 2020). Aeration makes the soil environment oxic, which results in the oxidation of CH_4 by the methanotrophs, causing a decrease in CH_4 emission. It is reported that up to 80% of the CH_4 produced during the rice-growing season is oxidized by the methanotrophs (Islam et al., 2020).

These results are in agreement with those of Corton et al. (2000), who conducted 9 experiments for 5years and found the CH_4 emission at a given treatments was higher during the wet season by 2 to 3 times the emission during the dry season. The methane emission was in the range of 67–120 kg CH_4-C ha^{-1} in dry season and 200–389 kg CH_4-C ha^{-1} in wet season. According to studies conducted by Hidayah et al. (2009) in Indonesia and Jain et al. (2014) in India the SRI methods reduced the methane emission up to 60 and 64%, respectively compared to conventional puddled transplanted rice.

Increased methane emission in CP treatments was due to formation of anoxic condition due to flooding moisture condition. Anoxic condition results in decreasing redox potential (−150 mV), which leads to the anaerobic decomposition of complex organic substrates by methanogens that finallydrive CH4 production (Islam et al., 2020). Higher

TABLE 8 Yield, season length, nitrogen rate and water management used as input values in SECTOR tool.

Treatments	N rates (t/ha)	Water management	Season length (days)		Yield (t/ha)	
			WS	DS	WS	DS
Combination						
SRI-ABC	0	AWD (alternate wetting and drying	127	129	4.5	4.8
SRI-0N	0	Irrigated -Multiple aeration	127	129	5.0	5.5
SRI-60N	60		127	129	7.0	6.4
SRI-90N	90		127	129	8.1	7.7
SRI-120N	120		127	129	7.4	6.6
SRI-150N	150		127	129	8.1	7.3
CP-ABC	0	CF (Irrigated-continuously flooded)	112	114	3.7	3.3
CP-0N	0		112	114	4.8	3
CP-60N	60		112	114	6.1	4.3
CP-90N	90		112	114	6.2	5
CP-120N	120		112	114	7.2	4.7
CP-150N	150		112	114	6.3	4.8

WS, wet season; DS, dry season.

TABLE 9 Seasonal methane and carbon dioxide emission as influenced by crop management practices and nitrogen fertilization rates.

Treatments	CH_4 Emission (kg ha^{-1} $season^{-1}$)		CO_2 Emission (kg ha^{-1} $season^{-1}$)		kg CO_2e $year^{-1}$
	WS	DS	WS	DS	
SRIABC	89.7ab	89.7a	827.7a	829a	6754a
SRI 0N	89.3ab	88.7a	827.3a	829a	6780a
SRI 60	89.7ab	89.3a	826.1a	829a	6729a
SRI 90	88.9a	89.0a	827.0a	829a	7009b
SRI 120	89.2ab	90.0a	828.3a	829a	7079b
SRI 150	89.7ab	89.8a	827.7a	829a	7159b
CP ABC	220.6c	183.3d	1033.3b	930.8a	14551d
CPN0	220.5c	183.3d	1034.7b	931.8b	14426d
CP 60N	90.7b	164.7c	0.0	0.0	8312c
CP90N	165.2b	165.2c	1032b	931.5b	12492c
CP120N	220.6c	183.3d	1034.7b	929.5b	14551d
CP150N	183.8b	100.7b	827.3a	930.1b	10341c
LSD 0.05	1.285	1.977	4.022	2.143	170.1
F Pr	<0.001	<0.001	<0.001	<0.001	<0.001

WS, wet season; DS, dry season.
Mean values followed by different letters denote significant ($P < 0.05$) difference between treatments by DMRT.

methane emission in CP may also be due to availability of organic substrate from root exudates and the reducing condition in the rice rhizosphere (Jain et al., 2014). The available organic carbon from root exudates increases the population of methanogen in flooding condition (Kumaraswamy et al., 2000).

Researchers around the global have reported different amount of methane emission from rice cultivation; this could be due to different in climate, soils, water management, verities, cultivars, fertilizer management and others. A study by Kim et al. (2012) reported the low seasonal methane emission of 126.8 from SRI plots compared to 458.4 kg C ha^{-1} from conventional flooding. According to Jain et al. (2014), the cumulative emission of CH_4 during the cropping period was lowest (8.16 kg ha^{-1}) in the SRI and the highest (22.59 kg ha^{-1}) in conventional method of transplanting method.

TABLE 10 Seasonal nitrous oxide emission (kg N ha^{-1} $season^{-1}$) as affected by management practices and nitrogen rates.

Treatments	Wet season	Dry season
SRIABC	<0.0000	<0.0000
SRI0	<0.0000	<0.0000
SRI60	0.0001	0.0001
SRI90	0.0001	0.0001
SRI120	0.0002	0.0002
SRI150	0.0002	0.0002
CPABC	0.0000	0.0000
CP0	0.0000	0.0000
CP60	0.0000	0.0000
CP90	0.0000	0.0000
CP120	0.0000	0.0000
CP150	0.0000	0.0000
F Pr	NS	NS.

NS, not significant.

Effects of crop management practices and nitrogen rates on carbon oxide emission

Seasonal carbon dioxide emissions ranged from 0.0 to 1,034 kg $ha^{-1}season^{-1}$ in both season and was significantly affected by treatment interaction (Table 9).CPN0 and CP120N had the highest seasonal cumulative flux and was significantly different from all other treatments. Except the treatment, CP60N recorded no seasonal flux for CO_2. System of rice intensification reduced CO_2 emission by 25%. Yearly CO_2 emission was higher in conventional treatments compared to SRI treatments. Carbon dioxide emissions are influenced by the crop residue and litter content, root activities, and microbial processes because the soil carbon pool is converted into CO_2 by the action of soil microorganisms. In the availability of water and urease enzymes, urea fertilizer applied in the fields converted to NH_4^+, OH−, and HCO_3, and this bicarbonate finally evolves into CO_2 and water (Hussain et al., 2015; Gupta et al., 2021).

Effect of crop management practices and nitrogen rates on seasonal emission of nitrous oxide

Seasonal nitrous oxide emission was in the range of no detected amount to 0.0002 kgN_2O ha^{-1} (Table 10). There were similar trends in emissions in both seasons where the emission of up to 0.0002 kgN_2O ha^{-1} was recorded in SRI treatments. Whereas SRI ABC and SRI0 treatments no amount of nitrous oxide captured by the tool. The tool captured the zero amounts (0.0000 kg ha^{-1}) in the CP treatment. Results are in agreement with that of Karki et al. (2021) in their study reported that N_2O emissions are generally low in flooded rice fields as most of the nitrogen is lost as N_2 rather than N_2O.

Zero N_2O emissions in conventional practice could be contributed by immobilization and retention of N fertilizer in soil (Fuhrmanna et al., 2018). The zero N_2O fluxes could also be due to some of the nitrogen being lost through leaching thus reducing amount of nitrogen substrate available for N_2O emissions. Owino et al. (2020) in their study in Kenya also observed insignificant N_2O emissions during rice growing season when the soil was flooded. This could be due to formation of anoxic conditions in the flooded paddies which create suitable conditions for denitrification with major product of this process being nitrogen gas (N_2).

In this study the relative amount of N_2O (0.0002 kgN_2O ha^{-1}) was recorded in SRI treatments, this could be due to the effect of alternate wetting water management regime that allow the introduction of oxygen when the field is free from flooded water, aerobic soil conditions significantly reduce CH_4 emission (Linquist et al., 2015; Lagomarsino et al., 2016; Jiang et al., 2019; Karki et al., 2021).

Studies have reported increased nitrous oxide emission from SRI treatments due to the general relationship between N_2O and CH_4, that when fields are saturated CH_4 increases, CO_2 and N_2O decreases. However, when fields become drier, CH_4 emissions decrease and CO_2 and N_2O emissions increase. Slight increase N_2O emission in field managed under alternate wetting and drying irrigation has been documented (Ku et al., 2017; Li et al., 2018; Islam et al., 2020). This is due to the increased nitrification of ammonium during the dry period and the subsequent denitrification of NO_3- during re-wetting of dry soils, but the GHG emission still reduced due to reduction in methane emission. Jain et al. (2014) reported increase of emission of N_2O–N by an average of 22.5% in SRI methods over conventional transplanted method.

Variable range of nitrous oxide emission in rice ecosystems has been reported by scholars this could be due to different in climate, management practices, different in soils, fertilization programs, varieties and other factors.

Seasonal nitrous oxide emission of 0.000028 kg N_2O ha^{-1} from conventional plots and 0.074 kgN_2O ha^{-1} from SRI plots was reported by Kim et al. (2012) in Korea under nine season experiments. According to Jain et al. (2014) the seasonal integrated fluxes of N_2O– N were 0.69 and 0.90 kg ha^{-1} from conventional transplanted rice and SRI planting methods, respectively. Boateng et al. (2020) conducted a study in Ghana and reported the seasonal N_2O emissions ranged from 1.61 to 58.08 kg N_2O ha^{-1}, and Gitonga (2020) conducted a study in Kenya and found the seasonal N_2O emissions ranged from 0.18 to 1.29 kgN_2O ha^{-1}. Hadi et al. (2010) in Indonesia reported the average N_2O emissions of 1.97 from intermittently drained plots and −19.7 kgN_2O ha^{-1} from continuously flooded plots respectively.

TABLE 11 Global warming potential, grain yield and greenhouse gas intensity as affected by management practices and nitrogen.

Treatments	GWP (kg CO_2e ha^{-1} season^{-1})		Yield (kg ha^{-1})		GHGI (kg CO_2e kg^{-1} paddy)	
	WS	DS	WS	DS	WS	DS
SRIABC	3367a	3407a	4500	4800	0.73b	0.7^{ab}
SRI 0N	3370a	3408a	5000	5500	0.65b	0.62^{ab}
SRI 60	3453b	3487a	7000	6400	0.45a	0.54^{ab}
SRI 90	3478b	3517a	8100	7700	0.42a	0.45^{a}
SRI 120	3520b	3560a	7400	6600	0.46ab	0.8^{abc}
SRI 150	3560b	3600a	8100	7300	0.42a	1.01^{abc}
CP ABC	7843c	6709b	3700	3300	2.04c	1.5^{c}
CPN0	7780c	6645a	4800	3000	1.62b	1.89^{d}
CP 60N	3114 a	5199a	6100	4300	0.52b	0.99^{abc}
CP90N	6298c	6193a	6200	5000	1.03c	1.29^{bc}
CP120N	7843c	6709b	7200	4700	1.06b	1.19^{abc}
CP150N	6606c	3737a	6300	4800	1.03c	0.76^{abc}
LSD 0.05	4.22	6.6	0.356	0.774	0.06037	0.7612
F Pr	<0.001	<0.001	NS	NS	<0.001	0.021

GWP, Global warming potential; WS, wet season; DS, dry season; GHGI, greenhouse gas intensity. Mean values followed by different letters denote significant ($P < 0.05$) difference between treatments by DMRT.

Effect of crop management practices and nitrogen rates on global warming potential and greenhouse gas intensity

Global warming potential (GWP) was significantly $p < 0.001$ affected by combined treatments of crop management practices and nitrogen fertilization rates and was high in CP treatments in both seasons (Table 11). The GWPs in this study are in range of 3,114.0–7,843 kg CO_2-e ha^{-1}season$^{-1,}$ these range are within the range reported in other areas. Higher amount of 7,843, followed by 7,780 kg CO2e ha^{-1} season^{-1} was recorded in CP120N and CP NO respectively. Low GWP of 3,114.0 and 3,367 kg CO_2e ha^{-1} season^{-1} was recorded in CP 60N and SRIABC treatments. SRI lowered the GWP significantly due to low methane emission compared to the CP method. The reduction of GWP of up to 57.1% was recorded in SRI treatments over CP treatments. These results confirm that the total GWP in rice fields is solely determined by CH_4 emission. However the radiative forcing of N_2O is much higher than CH_4, but the magnitude of N_2O emissions is very small. Thus, CH_4 is the major contributor of GWP in rice cultivation, representing over 90% of the total GWP (Sander et al., 2014; Janz et al., 2019; Islam et al., 2020). The reduction of GWP has been reported in SRI methods by Jain et al. (2014) reported the reduction of 29% in SRI methods over the transplanted puddled rice method.

Pramono et al. (2020) reported the highest GWP of 8,270 kg of CO_2-e ha^{-1}season^{-1} and lowest GWP of 4,240 kg ha^{-1} season^{-1}. Hadi et al. (2010) reported Seasonal Global warming potential ranged from 10,162–38,381 GWP (kg C-CO_2 eq ha^{-1} season^{-1}).

Greenhouse gas intensity (GHGI) was in the range of 0.42–2.04 kg CO_2e kg^{-1} paddy, these are within the range reported by Ali et al. (2019). SRI 90 and SRI 150 treatments recorded low amount (0.42 kg CO_2e kg^{-1} paddy) and CP ABC recorded higher GHGI of 2.04 kg CO_2e kg^{-1} paddy. SRI lowered the GHGI significantly due to low methane emission compared to the CP method.

These results are in agreement with Win et al. (2020) who reported significant the range of GHGI values (1.4–7.4 kg CO_2e kg^{-1} paddy) under continuous flooding than under alternate to wetting and drying irrigation. Zhang et al. (2016) reported the GHGIs (kg CO2 eq. t^{-1} grain) ranged from 712 to 1,245 kg CO_2. t^{-1} grain.

Effect of crop management practices and nitrogen rates on grain yield and yield components

Grain yield

The interaction of crop management practices and the nitrogen fertilization rate did not affect yield significantly ($p >$ 0.05), however there was percentage increase in grain yield of 44 and 61 in SRI plants during wet and dry season respectively (Table 11). The average grain yield in treatment interaction was in the range of 4.5–8.1 t ha^{-1} and 3.0–7.7 t ha^{-1} during wet and

TABLE 12 Effects of crop management practices and fertilizer N levels on panicle components of rice.

Parameter	Panicle weight (g)		panicle length (cm)		Number of panicle $hill^{-1}$		Number of panicle m^{-2}		Spikelet $panicle^{-1}$	
Season	**WS**	**DS**	**WS**	**DS**	**WS**	**DS**	**WS**	**DS**	**WS**	**DS**
Crop management practices (CMP)										
SRI	4.5	3.9	22.8	23.1	14.5	14.1	232.2	226.0	146.1	153.6
CP	3.5	2.2	22.0	20.3	9.1	11.0	228.1	274.2	113.5	86.9
Nitrogen levels (N)										
ABC	3.3a	2.7a	20.7a	20.4	8.7a	8.7a	175.1a	180.8a	118.5	103.0a
0 N	3.6a	2.7a	21.3ab	20.8	8.8a	9.9a	174.3a	189.3a	119.7	100.0a
60 N	3.7a	3.3ab	22.3ab	22.7	12.7b	13.5b	246.3b	263.0b	123.0	138.1b
90 N	4.3ab	3.6b	22.7bc	22.8	13.2b	14.6b	250.2b	285.0b	136.4	143.3b
120 N	4.8b	2.8a	24.4c	21.1	13.6b	14.4b	264.8b	294.1b	146.3	107.5a
150 N	4.2ab	3.1ab	23.0bc	22.4	13.8b	14.2b	269.9b	288.2b	135.0	128.7ab
Interaction (CMP x N)										
ABC	3.9	3.2	20.9	21.2	9.6abc	8.3	153.6	133.3	136.1	118.9
0 N	4.1	3.5	22.2	22.4	10.3bc	12.9	165.3	206.9	138.3	126.1
60 N	4.0	4.0	22.7	23.7	16.0d	14.7	256	267.7	142.0	168.2
SRI 90 N	5.0	5.1	23.5	24.9	17.7d	17.6	283.7	281.6	162.8	199.1
120 N	5.5	3.6	25.1	22.4	16.5d	14.5	264.5	231.5	165.3	135.5
150 N	4.3	4.1	22.8	24.1	16.9d	14.7	269.9	234.7	132.2	173.6
ABC	2.7	2.1	20.6	19.6	7.3a	9.1	196.7	228.3	100.8	87.1
0 N	3.1	2.0	20.4	19.2	7.9ab	6.9	183.3	171.7	101.1	75.1
60 N	3.4	2.6	21.9	21.6	8.7abc	10.3	236.7	258.3	104.0	108.0
CP 90 N	3.5	2.2	21.8	20.7	9.5abc	11.5	216.7	288.3	109.9	87.5
120 N	4.1	1.9	23.7	19.7	10.6bc	12.3	265	356.7	127.2	79.6
150 N	4.0	2.1	23.3	20.7	10.8c	13.7	270	341.7	137.7	83.7

Mean values followed by different letters denote significant ($P < 0.05$) difference between treatments by DMRT. WS, wet season; DS, dry season.

dry season respectively. Average grain yield in SRI treatments (SRI-60N, SRI-90N, SRI-120N, SRI-150N) recorded the yield potential range for TXD 306 variety which (7–8 t ha^{-1}) during wet season, while in CP only CP120N treatment reached the yield potential.

The increment in grain yield in the SRI treatment was largely attributed to increases in the number of spikelets per panicle and filled grain percentage (Table 12), the same was reported by other scholars. The yield in SRI plants could also be linked with the root characteristics i.e., higher volume and root weight (data not shown). Our results are in agreement with previous studies of other researcher's, such as Sandhu et al. (2017) reported strong association of root traits such as nodal root number, root dry weight with grain yield. Ashraf et al. (1999) reported that old seedlings results in CP practice lower rice yields because they suffer from stem and root injury during pulling. Previous studies in the study area with the same variety have reported different rice yield. Kahimba et al. (2013) reported 2.96–4.76 t ha^{-1} and yield increased by 24.3% in SRI compared to conventional practices and Reuben et al. (2016) reported grain yield ranged in 8.1–8.5 t ha^{-1} under SRI with the same variety.

Thakur et al. (2014) found overall, grain yield with SRI was 49% higher than with CP, with yield enhanced at every N application dose. Thakur et al. (2021) reported increased rice yield by SRI up to 25–50% or more and Mati et al. (2021) in Kenya reported the increased rice yields in the range of 20–100%.

Yield components

The number of panicles per hill was significant with SRI recording 37 and 22% higher than the CP in wet and dry seasons. Nitrogen levels and interactions with SRI or CP significantly affected the number of panicles (Table 12). The higher panicle weight percentages of 22.2 and 43.6% were recorded under SRI in wet and dry seasons, respectively. Panicle weight increased with an increase in N levels but not beyond 120 kg N^{-1} in wet season and 90 kg N ha^{-1} dry season. Panicle length was significantly ($p < 0.05$) affected by N levels and the length increased with increasing N levels in wet season. The number of panicle per hill was significantly ($p < 0.05$) affected by crop management practices in wet season, with SRI recording higher

TABLE 13 Effects of crop management practices and N levels on straw yield, harvest index, grain yield and 1,000 grains weight of rice.

Treatment	Straw yield (t ha^{-1})		Harvest index		1,000 grains weight (g)	
Season(s)	WS	DS	WS	DS	WS	DS
Crop management practices (CMP)						
SRI	5.1	3.9	0.6	0.6	32.8	29.8
CP	4.5	2.6	0.6	0.6	38.1	31.2
Nitrogen levels						
ABC	2.9a	2.2a	0.6b	0.7	33.9	28.8
0	3.0a	2.9ab	0.6b	0.6	33.9	30.5
60	4.9b	3.0ab	0.6b	0.7	35.7	30.9
90	5.6bc	3.8bc	0.6b	0.6	37.8	32.5
120	6.0c	4.1c	0.6b	0.6	37.7	30.9
150	6.6c	3.5bc	0.5a	0.6	33.8	29.5
Interaction (CMP x N)						
ABC	3.2	2.8	0.6b	0.6	32.9	26.9
0 N	3.6	3.5	0.6b	0.6	32.8	30.5
60 N	5.2	3.5	0.6b	0.6	32.6	30.4
SRI 90 N	6.2	4.8	0.6b	0.6	32.9	33
120 N	5.8	4.8	0.6b	0.6	32.7	31.2
150 N	6.5	3.9	0.6b	0.7	32.8	26.9
ABC	2.6	1.6	0.6b	0.7	34.9	30.8
0 N	2.4	2.3	0.7bc	0.6	34.9	30.4
60 N	4.6	2.5	0.6b	0.6	38.8	31.5
CP 90 N	4.9	2.8	0.6b	0.6	42.6	31.9
120 N	6.2	3.4	0.5a	0.6	42.6	30.6
150 N	6.6	3.1	0.5a	0.6	34.9	32

Mean values followed by different letters denote significant ($P < 0.05$) difference between treatments by DMRT; WS, wet season; DS, dry season.

number of panicle per hill (15) compared with CP (9). Nitrogen levels and their interactions with SRI or CP significantly affected the number of panicles per hill. Spikelets per panicle were significantly influenced by crop management practices, with SRI recording higher number of spikelets per panicles in wet and dry seasons. Nitrogen levels also significantly affected the number of spikelets per panicle during dry season.

Effective tillers were significantly affected by CP, N levels and their interactions ($p < 0.05$) in wet and dry seasons but SRI recorded higher effective tillers over CP (Table 12). The filled grains per panicle were significantly affected by crop management practices ($p < 0.05$) in wet and dry seasons. Grain filling rate was significantly affected by crop management practices in wet season, with increased grain filling by 4.6 and 5.9% under SRI compared with CP in wet and dry season, respectively. There was significant effect of N levels in dry season. Previous studies have reported absence of significant effect of crop management practices on percentage of filled grains (Belder et al., 2004; Zheng et al., 2020).

The CMP significantly affected straw yield during dry season and SRI recorded increased straw yield by 33.3% over CP (Table 13). Straw yield increased with increase in N levels in wet and dry seasons. The highest straw yield was recorded in wet season (6.6 and 6.5 t ha^{-1}) in an application of 150 Kg N ha^{-1}, and with interactions of SRI and CP with 150 kg N ha^{-1}. Harvest index (HI) was significantly affected by N levels during wet season, whereas the lowest HI of 0.5 was recorded in an application of 150 kg N ha^{-1}. There was no interaction effects observed between treatments on the straw yields. Results also indicated that the dry weight of 1,000-grains was significantly affected by CP in wet season. However, there was no significant effect of N levels or their interactions with CP or SRI observed on the dry weight of 1,000 grains. Crop management practices significantly affected panicle weight and spikelets per panicle in wet and dry seasons, with higher values recorded under SRI.

Conclusions

Our results show that the treatments interaction of system of rice intensification and nitrogen rates significantly decreased CH_4 and CO_2 emissions from paddy rice in either rice seasons.

Conventional practice contributed to higher GWP and GHGI. System of rice intensification treatment reduced global warming potential, methane and carbon dioxide by 57.1, 59.2, and 25% over CP treatments, respectively. System of rice intensification and nitrogen fertilization at 90 kg N ha^{-1} could be practiced to sustain increase rice productivity while minimizing greenhouse gases intensity in the changing climatic conditions.

Our results suggest strong potential for system of rice intensification management practice to reduce the total GHG emissions from paddy rice, while maintaining rice yield.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author/s.

Author contributions

PAM set and managed experiments, collected data, and analyzed and wrote the first draft of manuscript. KK and AA reviewed and edited the manuscript. PM collected data, managed experiment, and reviewed first draft of manuscript. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2022.868479/full#supplementary-material

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Gender perspectives of the water, energy, land, and food security nexus in sub-Saharan Africa

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The water, energy, land and food (WELF) nexus has been touted as a cross-sectoral systems approach that presents an opportunity to address the grand challenges related to poverty, unemployment, inequality and climate change, especially in the global South. However, as with any other developmental approach, the WELF nexus needs to mainstream gender, which often lies at the heart of poverty, unemployment, and inequality in sub-Saharan Africa. Access to water, energy, land and food is gendered, and so are livelihood strategies and climate change responses. Inequitable access to these resources, gender inequalities, socio-economic vulnerability and cultural norms contribute to women's susceptibility to the impacts of climate change and limit their ability to harness opportunities arising from it. Reducing women's vulnerability to the impacts of climate change in SSA and improving equity in natural resource access and resource use efficiencies will require transformation of gender relations and the active participation of both men and women in decision-making processes. Moreover, policies and interventions that cater to the WELF nexus need be updated to be more gender-aware and sensitive, as this will also contribute to addressing Sustainable Development Goal 5, in addition to Goals 1, 2, 6, 7, and 15.

KEYWORDS

poverty alleviation, livelihoods, climate change adaptation, gender-responsive planning, natural resource access

Introduction

Water, energy, and land are important for many life supporting functions and the provision of basic human needs (German Development Institute, 2013). These resources are crucial contributors to food security and development (German Development Institute, 2013; Ringler et al., 2013). Due to growing natural resource scarcity, the inter-linkages that exist between these sectors have become more pronounced, as evidenced by growing trade-offs and the search for cross-sector efficiencies (Ringler et al., 2013). Access to these resources and their sustainable management are the basis for inclusive sustainable development, and poverty reduction (German Development Institute, 2013).

However, resource access for the poor in sub-Saharan Africa remains both a practical and policy challenge, and inequitable access to basic resources is especially prevalent among women (Villamor et al., 2018). Women's access to water, energy, land, and food resources in sub-Saharan Africa is further explored in this chapter.

The interdependencies that exist between water, energy, land and food are numerous and multidimensional, and these interlinkages are referred to as the water-energy-land-food (WELF) nexus (Ringler et al., 2013; OECD, 2018; GWP SA, 2019). These resources are crucial to human existence and how they are governed affects outcomes in terms of social equity, externalities, and socio-ecological resilience (Albrecht et al., 2018). Moreover, sector policies for these resources are intertwined, in particular, in their trade-offs (German Development Institute, 2013). Policies for one sector often bear consequences or negative externalities for the other three sectors, on local, national, regional or global scales (German Development Institute, 2013; Serdeczny et al., 2017; OECD, 2018). These interlinkages add to current pressures on water and land as well as on resources that fuel the energy system, exacerbating existing scarcity problems, as the demand for food, water and energy is expected to increase by 30–40 percent by 2030 (German Development Institute, 2013). Therefore, the implementation of the nexus requires policies, institutional arrangements and procedures that can take these trade-offs and synergies into account (German Development Institute, 2013). Failure to do so will generate high costs to the economies of SSA and exacerbate inequalities across countries and social groups, both now and in the future (OECD, 2018).

Water plays a crucial role in food and energy production [especially hydro-energy production which is a major source of energy in southern Africa (Nhamo et al., 2018), and in sustaining the ecosystems that support agriculture and other economic activities that are important for achieving food security (GWP SA, 2019)]. Energy is necessary for food production and for water supply (including the extraction, purification, and distribution of water) (Nhamo et al., 2018; GWP SA, 2019). Interactions among these nexus components play a vital role in the living standard outcomes of marginalized households, and can be captured and/or affected through changes in household behaviors or activities (Villamor et al., 2018). Access to, control over, and the use of WELF resources are also influenced by gender, however, not many studies have taken this into consideration nor have they addressed the potential for differential effects of WELF nexus interventions with respect to gender (Villamor et al., 2018; Khadka, 2022; Sani and Scholz, 2022). Women, who constitute two-thirds of the world's poor, are key stakeholders in nexus sectors, however, they face significant structural barriers (Khadka, 2022; Sani and Scholz, 2022). Moreover, the working culture in these sectors is still guided or influenced by masculine attitudes, behaviors, and mindsets and women struggle to access these men-dominated spaces (Khadka, 2022). Very little effort is made to understand and tackle systemic gender issues related to water, energy, land, and food within the nexus sectors (Khadka, 2022). This is evidenced by the fact that global discussions on the WELF nexus have under-represented the linkages that exist between gender and the nexus (Villamor et al., 2018; Purwanto et al., 2021). The linkages refer to women's access to, and their role in the utilization of these resources. For example, women are responsible for providing food for their households in addition to fetching fuelwood for cooking and potable water, which are unpaid productive activities (Villamor et al., 2018). Moreover, the majority of agriculturalists in SSA are women (Ruiters and Wildschutt, 2010; Villamor et al., 2018), and easy and equitable access to these resources will promote women's socio-economic development while contributing toward gender equality. Therefore, gender is relevant to the WELF nexus agenda and should be taken into account, especially at the local level. Climate change exacerbates insecurities of WELF resources, while changes in the availability of these resources, access, and security, shapes the manner in which individuals, communities and countries respond to the changing climate (Sultana, 2018). Social differences such as gender and class impact the ways in which the impacts of climate variability and change are experienced and responded to (Sultana, 2018). Against this backdrop, this article seeks to explore the interlinkages that exist between the WELF nexus and gender and how these interlinkages can facilitate greater and more effective climate change response strategies and resource use efficiencies in sub-Saharan Africa. Policies and interventions that cater to the WELF nexus need be updated to be more gender-aware and sensitive. This will also contribute to addressing Sustainable Development Goals 1 (no poverty), 2 (zero hunger), 6 (clean water and sanitation), 7 (affordable and clean energy), and 15 (life on land), in addition to Goal 5 (gender equality).

Research methods

The study used secondary data to review literature on gender and the water, energy, land, and food security nexus in sub-Saharan Africa. The literature focussed on six main themes, which became the search terms. These themes were:

- Gender and water in sub-Saharan Africa
- Gender and energy in sub-Saharan Africa
- Gender and land in sub-Saharan Africa
- Gender and food in sub-Saharan Africa
- Gender and climate change in sub-Saharan Africa
- Climate change and WELF resources.

The literature published in academic and non-academic sources was assessed, including journal articles, book chapters and gray literature. The databases used for the search were Google and Google Scholar. The findings were then reported under the various themes.

The majority of literature found in the study focused solely on women, despite a focus on gender. A similar finding was found by Pouramin et al. (2020) who conducted a systematic review on gender and water. The authors reported that nearly half the studies (46%) focused exclusively on the experience of women and girls and did not consider impacts on men.

Gender and WELF nexus resources in sub-Saharan Africa

Gender and water

Access to improved water and sanitation are important human rights, however, 780 million people lack access to safe water and one third are experiencing some form of economic or physical water scarcity (IFAD, 2012; German Development Institute, 2013; Armah et al., 2018). Access to improved water sources has increased over the last 30 years in the SSA, however, this access is gradually being eroded due to the region's high rates of population growth and urbanization (Dominguez et al., 2012; Ahmed, 2018; Armah et al., 2018). The high population growth and urbanization rates have not been accompanied by economic growth or investment in housing, water, and sanitation infrastructure (Armah et al., 2018). Furthermore, climate change is compromising the provision of water supply services in the region resulting in more frequent droughts and water shortages (Dominguez et al., 2012). Amidst these challenges, there is also growing competition for water within different sectors, making it increasingly difficult for people, especially marginalized women, who are the primary users, providers and managers of water in their households, to access the resource for productive, consumptive and social purposes (WSP, 2010; IFAD, 2012; Jong et al., 2013). The sectors competing for water include industry, agriculture, power generation, domestic use, and the environment (IFAD, 2012; Jong et al., 2013).

Women and men have differential roles, rights and responsibilities with regards to water (Ahmed, 2018). Women face inequity in access to water resources, despite the fact that they are primarily responsible for the management of household water supply, sanitation and health (Allély et al., 2000; Armah et al., 2018; Pouramin et al., 2020; UN, 2018). For example, in schools in Malawi and Ethiopia, girls lack access to adequate sanitation and hygiene in the form of clean water supplies and sufficient latrines (Fleifel et al., 2019). Moreover, women and girls in rural areas are forced to walk long distances to fetch water, preventing them from undertaking other activities or participating in education (Palacios-Lopez et al., 2017; Ahmed, 2018; Pouramin et al., 2020). For example, in Mauritania, Somalia, and Tunisia, an average distance of a trip to collect water is 4-5 kms and takes 33 mins each way (Connell, 2017). The physical security of the women and girls is also threatened during their walk as they generally travel long distances, on unsecured paths, alone, leaving them vulnerable to sexual violence and attacks (Fleifel et al., 2019). It is estimated that more than two-thirds of the SSA population leave their homes to collect water, and the majority of rural water systems are often non-functional, making water collection even more difficult (Palacios-Lopez et al., 2017).

Access to water is invariably linked to sanitation and hygiene. Therefore, inequitable access to water can lead to poor sanitation and health burdens for women (WaterAid Canada, 2017; Pouramin et al., 2020). Given their traditional role as water purveyors, sexual and reproductive health needs, and their role as caretakers within the household, access to clean water and sanitation is of great importance to women and girls (WaterAid Canada, 2017). If the water is contaminated with infectious microorganisms, the risk of contracting waterborne diseases such as cholera is higher, and women are at higher risk of contracting and transmitting this disease due to their water provisioning role (Pouramin et al., 2020). Similarly, women can contract urinary tract infections (UTIs) due to poor menstrual health management which is often due to the failure to access the additional resources required for good menstrual health (Pouramin et al., 2020). This can lead to girls missing school and overall reduced education (Pouramin et al., 2020), or women missing out on income generating opportunities (WaterAid Canada, 2017). Carrying buckets of water for protracted periods of time can also lead to fatigue and back and arm injuries. As transporting water takes up considerable time and energy, it places high demands on the metabolism, and can result in pressure on the skeletal system leading to early arthritis (Palacios-Lopez et al., 2017). Therefore, water transporters are vulnerable to musculoskeletal damage and early degenerative bone and soft tissue damage which may compromise their ability to access water in the long-run (Palacios-Lopez et al., 2017). The provision of water sources in proximity to households would make water collection more efficient and improve domestic and personal hygiene (Palacios-Lopez et al., 2017). Some authors have also found that hygiene practices and hygiene-related health outcomes are directly related to how far the water source is from a household (Palacios-Lopez et al., 2017). People who are denied access to improved water and sanitation services face "diminished opportunities to realize their potential" (Armah et al., 2018, p. 2).

Securing water and sustained access to water are important for achieving food security and improving the rural livelihoods in SSA. Women play a fundamental role in food security through their knowledge of crop production, local biodiversity, soils and local water resources (Jong et al., 2013). Women make substantial contributions to the rural economy of SSA as farmers, laborers and entrepreneurs, comprising at least

40% of the agricultural labor force in the region (Palacios-Lopez et al., 2017). However, they are often excluded from decision-making processes regarding water and new agricultural water management systems and other projects and initiatives concerning the allocation of natural resources (Jong et al., 2013). Excluding women from decision-making processes results in resources being less accessible to them and important issues such as menstrual hygiene management, are viewed as niche issues and taboo (WaterAid Canada, 2017). The women also lose out on opportunities to generate income, for example, agricultural activities which depend on the availability and accessibility of water (WaterAid Canada, 2017). It is important for both men and women to participate in decision-making in order to determine what they need, if they can make any contributions and in what capacity (Jong et al., 2013). Gathering information on the experiences and knowledge of both men and women will allow for a better understanding of existing practices and challenges, and help to identify the problems that need to addressed first (Jong et al., 2013). This will also lead to better investment decisions (Jong et al., 2013). The involvement of both men and women will also help to identify any conflicts that might exist between different socio-economic and ethnic groups and ways can be found to prevent or solve them (Jong et al., 2013).

Securing women's access to water is crucial to tackling two goals of sustainable development, i.e., Sustainable Development Goals (SDGs) 5 (gender equality) and 6 (clean water and sanitation). The water and sanitation sector has the potential to contribute to redressing inequality and can greatly improve the social, political and economic position of women (WSP, 2010). Providing women with sufficient access to improved water sources tackles time poverty by freeing up the women's time to allow them to participate in social, economic, and political activities, and decision-making (WSP, 2010; Ahmed, 2018). Armah et al. (2018) assert that compositional factors such as the household head's sex, age, and level of education, and the size of the household contribute significantly to the disparities in access to improved water sources and sanitation facilities in SSA (Armah et al., 2018). Female-headed households in SSA are more likely to advocate for access to improved water sources and sanitation due to their roles within the household, and are likely to pay more attention to such issues than men (Armah et al., 2018). Therefore, it is important that gender is mainstreamed into any programme, policy, initiative or discussions about water. Gender mainstreaming is strategy to promote gender equality and women empowerment at all levels of development by ensuring that gender perspectives are central to all activities (UN Women, 2014). These activities include policy development, research, advocacy/ dialogue, legislation, resource allocation, and planning, implementation and monitoring of programmes and projects equality (UN Women, 2014). There is also need for capacity building and bottom-up approaches, which can also help to build social capital and support autonomous adaptation efforts (Ahmed, 2018). In addition, in order to tackle the impacts climate change will have on water provision, flexible, adaptable, and gender-conscious solutions are required as well as the design and development of water supply infrastructure which can withstand the changes and reduce the vulnerability of systems (Dominguez et al., 2012).

Gender and energy

The energy sector is a key driver behind a number of critical environmental pressures, including anthropogenic greenhouse gas emissions (GHG) and land and water use and degradation (German Development Institute, 2013). It is estimated that energy-related emissions (including transportation, electricity and heat, buildings, manufacturing and construction, fugitive emissions and other fuel combustion) account for 73% of the global total GHG emissions (Ge and Friedrich, 2020). However, the sector is also undergoing tremendous external stress and changes due to several factors including climate change and the COVID-19 pandemic which has slowed down efforts to increase electrification rates as governments are prioritizing immediate public health concerns and economic crises (IEA, 2020). The energy sector in SSA is underdeveloped, making access to energy one of the region's greatest obstacles to social and economic development, at a time when the increasing populations and prospects of economic growth require more energy (Hafner et al., 2018). Energy use per capita in SSA is equivalent to one-third of the world's average and 25% of that of the Middle East and North Africa (Hafner et al., 2018). South Africa is the only country in the region whose per capita energy use exceeds the world average (Hafner et al., 2018). Across SSA, there are large disparities in per capita consumption between urban and rural areas, with cities enjoying better access to modern forms of energy (Hafner et al., 2018).

Energy poverty is one of the most critical development challenges in SSA as many people face inadequate and unreliable access to modern energy services and rely heavily on traditional biomass fuels such as wood, charcoal, dung, and agricultural wastes for cooking and heating (Lambrou and Grazia, 2006; Danielsen, 2012; Hafner et al., 2018). Energy poverty also has a strong gender element (OECD, 2021). It is estimated that 30% of households live in energy poverty, and 81% of SSA depends on woody biomass energy especially for cooking, household and economic activities (World Bank, 2011; Bildirici and Özaksoy, 2016; OECD, 2021). Unfortunately, the inefficient use of solid biomass fuel for cooking and lighting causes indoor air pollution which kills $\sim$600,000 people per year (Alstone et al., 2011; Hafner et al., 2018; Banerjee, 2019). Women and young children are the most affected by this pollution because they spend more time inside the house and next to the stove while food is being cooked (Hafner et al., 2018).

The majority of people who have no access to basic modern energy services reside in the rural areas of SSA. Such deprivation often has negative impacts on economic and social development, health, time education and fulfillment, and gender equality (Lambrou and Grazia, 2006; Danielsen, 2012; Hafner et al., 2018). Women and men play different gender-defined roles in energy production, distribution and utilization in households, communities and the market (UNDP, 2012), and women experience energy poverty differently and more severely than men (Alstone et al., 2011; Danielsen, 2012). However, energy policies in the region are gender blind (Johnson et al., 2019). People with no or limited access to energy tend to be generally poorer than those with energy access; they are less productive; face heavier work; are more exposed to health risks; and lack the benefit of modern technologies and communication (Hafner et al., 2018). For example, in rural areas, energy is the primary responsibility of women and they spend most of their days engaged in time-consuming and physically draining subsistence activities which include the fetching of water and biomass fuels (Lambrou and Grazia, 2006; Alstone et al., 2011; Danielsen, 2012; UNDP, 2012; Hafner et al., 2018; Johnson et al., 2019). This is time they should spend in school or on earning additional income or improving their labor productivity which can empower them and promote socio-economic development (EEP S&EA, 2017; Hafner et al., 2018). Unfortunately, due to a lack of information, awareness, and tangible action plans for development institutions and the private sector, the role of women in the energy sector is often overlooked in developing countries or misinterpreted (Alstone et al., 2011).

Access to energy is a human right, and gender impacts this right in two ways: supply (production) and consumption (Banerjee, 2019; Johnson et al., 2019). On the consumption side, women have major energy-consuming responsibilities in and around the household and community, while on the supply side, women in the rural areas of SSA, as mentioned earlier, play a major role in the production and procurement of energy, particularly, traditional fuels such as firewood and other woody biomass (Johnson et al., 2019). However, it is important that women and men have different energy requirements (Banerjee, 2019). For example, women may opt to place illumination devices in kitchen, while men may opt to place them in living room to facilitate social gatherings (Banerjee, 2019). Energy access tends to be determined by intra-household decision-making, the social position of women, and the value attached to women's labor (Danielsen, 2012; Banerjee, 2019). There is no economic value associated with biomass collection, therefore, there is a lack of recognition of this type of women's work, and the other multiple roles they fulfill in the household (Danielsen, 2012). Moreover, women's work in agriculture and as entrepreneurs has received limited recognition, while investments into improved cooking technology has not been prioritized at both the household and national levels (Danielsen, 2012). Studies have shown that access to electricity within the household has indirect but strong impact on women (Banerjee, 2019). For example, household electrification increased female employment and school attendance in rural areas, especially amongst teenage women (Banerjee, 2019), while in rural health centers, access to electricity has been instrumental in much safer child deliveries (Banerjee, 2019). Other reasons for the rights failures with regards to women's rights to energy is the fact many women lack control over land and property, which affects their ability to benefit equally to men from energy facilities, including, solar systems, wind turbines, and bio-fuel plantations, which require land (Danielsen, 2012). A study on access to electricity for business based in Ethiopia, Ghana, Kenya, Tanzania, and Zambia revealed that electricity connections for women-headed businesses are generally delayed when compared to their male counterpart (Banerjee, 2019). This discrepancy has major ramifications for self-employed women, and some of these women have to resort to paying bribes secure electricity connections (Banerjee, 2019). A lack of income also acts as a barrier for women to invest in technology that can significantly improve the productivity of their labor (Danielsen, 2012). Women lack access to credit which affects their ability to pay the up-front costs of improved energy technology or connection fees to the electricity grid (Danielsen, 2012). They also have limited access to extension services and education, limiting their abilities to become energy entrepreneurs and earn an income (Danielsen, 2012). Lastly, women internalize social norms that place a low value on their worth and contribution (Danielsen, 2012). This likely has a negative impact on their access to modern energy services, as well (Danielsen, 2012). Unequal gender and power relations can hinder women's ability to participate and voice their energy needs in decision-making at all levels of the energy system (Danielsen, 2012).

Energy is key to development and poverty alleviation (UNDP, 2012), and decision-making about its use has complex linkages with policies pertaining to poverty, food security, health, population, gender disparities, environmental quality, investments, foreign exchange, trade and national security (Lambrou and Grazia, 2006). However, despite a growing knowledge base on the linkages between gender, energy and poverty, international efforts to promote the energy rights of women are still inadequate, and the gender and rights failures are being replicated (Lambrou and Grazia, 2006; Danielsen, 2012). Gender equality tends to be viewed as a predominantly political issue, which is not related to technical concerns about energy production and supply (Lambrou and Grazia, 2006). Therefore, energy planners and policy-makers seldom consider women, and concerns about women are treated as 'added on' factors which are not directly relevant to energy issues (Lambrou and Grazia, 2006, p. 7). Moreover, the energy sector mostly employs men, with women mainly being considered as the beneficiary or customer (EEP S&EA, 2017). The rights failures within the energy system are reflective of the governance malfunctions at all levels (Danielsen, 2012). Therefore, in order to overcome the challenges associated inequitable access to energy, the energy system governance, policy and programmes need to address structural gender inequalities at the level of institutions (Danielsen, 2012).

It is necessary to mainstream gender in energy-related policies, programmes and initiatives at all levels of government (Lambrou and Grazia, 2006), and engage more women as grassroots workers in the electrification programmes (Banerjee, 2019). Policies need to illustrate that gender equality is a priority, while energy programmes and interventions should be designed to create opportunities for women's empowerment, and gender equality (Lambrou and Grazia, 2006). Women should be encouraged to participate in energy-related decision-making at the national, local and household levels, and at an organizational level, space and opportunities should be made available to both women and men (Lambrou and Grazia, 2006; Banerjee, 2019). Countries such as Zimbabwe and Rwanda are already working toward the increased representation of women in the energy sector (Banerjee, 2019). The Ministry of Energy and Power Development in Zimbabwe has identified a gender focal point to coordinate the implementation of gender mainstreaming in the energy sector, while the government in Rwanda, encourages women's participation in the planning, design and execution of energy programmes (Banerjee, 2019). As women are not a homogeneous group, it is also necessary to consider gender disparities within the particular social, economic and political contexts (Lambrou and Grazia, 2006). Factors such as culture, income, social class, religion, family status and geographical location need to be taken into account in energy decision-making (Lambrou and Grazia, 2006).

Efforts to mainstreaming gender into energy approaches need to go beyond a focus on technological changes such as replacing candles and traditional cookstoves with cleaner and more efficient alternatives, or meeting the immediate or practical needs of women that affect their daily lives and practices (Johnson et al., 2019). It is also necessary to address the broader socio-cultural empowerment or strategic' needs required to transform gender divisions of labor, power, and control, need to be addressed (Johnson et al., 2019). Adopting people-centered, gender-differentiated approaches to energy planning guarantees that women and men have equal opportunities to access, participate, and benefit from en-ergy sector initiatives (EEP S&EA, 2017). This will also help to tackle two goals of sustainable development, i.e., Sustainable Development Goals (SDGs) 5 (gender equality) and 7 (affordable and clean energy). This requires the development and implementation of initiatives that integrate gender equality into affordable clean energy programmes and ensuring that the benefits of affordable clean energy also contribute to gender equality (EEP S&EA, 2017). The participation of women in decision-making, and the design, distribution, management, and production of sustainable energy solutions improves development outcomes (Johnson et al., 2019), and.is essential to the realization of the goals of sustainable development goals (EEP S&EA, 2017). Gender-sensitive energy programmes can also ease the double burden of lack of sufficient energy and poverty that women, especially rural women, face as they perform traditional household and community roles (Lambrou and Grazia, 2006). Meeting the energy needs of women can lead to improved health and wellbeing of entire communities; provide them with opportunities for education and income generation, thereby improving their social and economic statuses, while improving the standard of living for themselves and their families and communities, and greater security (Lambrou and Grazia, 2006; Johnson et al., 2019). Capacity development and the establishment of a monitoring system to assess the progress toward eliminating energy poverty and gender mainstreaming is necessary as this can improve women's access to energy and improve accountability to women's energy rights (Danielsen, 2012). Access to affordable, sustainable and clean energy is necessary for gender equality and wellbeing (OECD, 2021).

Gender and land

Land is a productive asset and an immovable factor of development which serves as a major source of wealth for the poor, and plays a key role in social relationships (Akinola, 2018; Chigbu, 2022a; Murphy and Fogelman, 2022). In sub-Saharan Africa, the issues women face regarding equal access to, ownership of, and control over land are complex (IIED, 2015), despite the fact that, after the 1990s, land reforms in countries in the region started incorporating gender aspects in legal provisions to protect women's land rights (Ghebru, 2019). This complexity is attributed to the fact that individual property rights co-exist with customary laws and the majority of agricultural land is not registered and does not have formal ownership documents (Slavchevska et al., 2020). In rural areas, customary tenure regimes, which are driven by lineage or clan control, shape people's access and ownership of land (Goldstein et al., 2016; Akinola, 2018; Massay, 2019). These laws tend to favor men, therefore, women, are less likely than men to own land, even when they make a significant contribution to agricultural labor (Jong et al., 2013; Goldstein et al., 2016; Massay, 2019), and where they do own land, the plots are usually smaller than those owned by men and are often of poorer quality (FAO, 2011; IIED, 2015). Women can likely gain "secondary" land use rights, which are undocumented, through a male spouse or relative, however, in the event of divorce or the spouse's death, they can lose these rights (Goldstein et al., 2016; IFAD, 2013). Widows are the most likely to lose their land and other assets, further disempowering them and their children (Akinola, 2018). The lack of tenure security means that women, in particular, widows and female-headed households, are amongst the most vulnerable in society (IFAD, 2013). Given the role of women in household subsistence production and welfare, steps need to be taken to strengthen their rights to land, thereby contributing toward gender equality and poverty reduction (IFAD, 2013), Sustainable Development Goals (SDGs) 5 and 1, respectively.

There are several female-headed households in SSA due to the death of husbands, high rates of divorce, and the prevalence of 'single motherhood' in countries such as South Africa. These households are in need of land resources as economic and productive assets (Akinola, 2018). Secure access to, and ownership of land are necessary for the improvement of women's socio-economic status, well-being, and self-esteem (Akinola, 2018; Massay, 2019; Slavchevska et al., 2020; IFAD, 2013). Studies have revealed that gender-equitable division of land has numerous benefits, including (i) increased rural productivity, (ii) increased bargaining power within the household, (iii) reduced domestic violence, (iv) improved child nutrition and health, and (v) improvements in household welfare (IIED, 2015; Massay, 2019; Slavchevska et al., 2020). Women tend to spend a larger portion of household income on food, therefore, any increase in female landholdings will lead to an increase in the amount of income spent on food and child education (Massay, 2019), which will have positive impacts on the household. Massay (2019) reports that the children of women who own land are less likely to be severely underweight because the women oversee household decisions. As a result of these benefits, some countries in the region have started incorporating gender-equitable land governance into their national legal frameworks (IIED, 2015). For example, in Senegal, the national law states that "men and women have equal right to access and ownership of land" (IIED, 2015, p. 3), and in Ghana, the Land Act 2020 (Act 1036) prohibits discriminatory practices based on gender, and calls for gender considerations to be taken into account when staffing the Customary Land Secretariat (Republic of Ghana, 2020). In Kenya, the Constitution advocates for the "elimination of gender discrimination in law, customs and practices related to land and property in land" (IIED, 2015, p. 3), however, implementation of the law has not yielded much success with respect to women's ownership of land (Akinola, 2018). Chigbu (2022b) notes that while policy articulation by the government on the rights of women farmers has shifted, and progressive changes are being made, we are far from a deep change and exclusionist attitudes to making decisions still exist. Securing women's land rights is a complex process, especially where sociocultural patterns, structural and economic impediments, and power imbalances hinder efforts (IIED, 2015; Akinola, 2018). Some households may overlook national laws regarding gender equality and uphold their traditional practices which greatly disadvantage women. Moreover, many women in SSA have limited access to credit facilities and lack the financial means to purchase land (Akinola, 2018).

Any efforts to secure land rights for women and tackle gender inequalities in land governance need to consider local contexts and gender dynamics, and move beyond generalizations about customary practices and seek opportunities promote women's voices and decision-making power (IIED, 2015; Massay, 2019; Chigbu, 2022b). Within these households or families, the person who decides on land management and participates in community meetings has the decision-making power (IIED, 2015). Unfortunately, women are seldom involved in decision-making processes concerning land. While gender inequalities around land governance are predominantly linked to women's capacity to hold and inherit tenure rights, they are also a result of women's lack of participation in decision-making processes concerning land and gender discrimination in sociocultural and political relations (IIED, 2015; Massay, 2019). Moreover, many national and international discussions about land, including commercial pressures and 'land grabbing', are gender blind and have very little input from or representation of women, in particular, rural women (IIED, 2015). The focus of some of these discussions is on the needs of rural women in terms of equal access to and control over land, however, the voices and opinions of these women are often not included (IIED, 2015). Exclusionist land governance systems cannot achieve the expected development dividends that would enable the fulfillment of the global development agendas (Chigbu, 2022b). Therefore, these discussions would benefit from the participation and involvement of rural women as they can provide an understanding of their specific needs around access to land and the main drivers behind these needs (IIED, 2015). Steps need to be taken to ensure the voices of women are heard. Time should also be taken to understand the context and identify some of the entry points women can use to claim their rights. These same entry points can then be utilized to support women's empowerment through exercising agency, while claiming and realizing their rights (Massay, 2019). Women's secondary rights to land also need to be recognized by governments as being equal to men's rights, spousal rights need to co-registered, and women's inheritance rights need to be recognized (IFAD, 2013). Furthermore, the process of land registration for women needs to be improved as Akinola (2018) states that some women in both urban and rural areas who have been granted access to land have struggled to obtain title deeds, while registration for such lands tends to be expensive for marginalized groups, and is very difficult. In countries such as Ethiopia, Ghana, Madagascar, land rights registration is subject to high costs and bribes (Ghebru, 2019). Unfortunately, women face similar challenges if they litigate or appeal land disputes (Ghebru, 2019). Ghebru (2019) asserts that in order for any formal land registration reform to be considered as gender-sensitive, the formal costs and fees associated with such reforms should be affordable, while informal costs, such as bribes, should be eliminated or discouraged. "Whether a governance system can deliver pro-poor and gender-balanced outcomes depends on its structure. It also depends on whether all the stakeholders involved in the gender continuum play their respective roles in land governance" (Chigbu, 2022a; p. 5).

Women from rural areas have launched activism campaigns to fight against rural gender discrimination related to land rights (Massay, 2019). For example, civil society organizations (CSOs) such as Kenya Land Alliance, Rwanda Land Alliance, Uganda Land Alliance, the National Land Forum in Tanzania, National Land Committee in South Africa, and the Namibian NGO Federation are advocating for the land rights of women, pastoralists, the landless and other marginalized people in their countries (Massay, 2019). It is important to note that women in urban areas (including townships, informal settlements or slums) tend to have more property rights than their rural counterparts (Akinola, 2018). This is largely because of the erosion of cultures and traditional norms in urban areas; the higher level of education; and the monitoring of legal provisions by government institutions (Akinola, 2018). For example, in Ghana, women in urban areas own 23% of couple's wealth, as opposed to 15% owned by rural women (Akinola, 2018).

Land tenure security is important for the socio-economic development of women in SSA. Securing land rights for women is also important for addressing agricultural production, and climate change mitigation and adaptation (Massay, 2019), as this will motivate them to utilize the land in a sustainable manner, while contributing to conservation efforts and livelihood strategies that are adapted to the changing climate, without fear of losing their land (Gioverelli and Scalise, 2016; Veit, 2019). However, the right to land is still denied to many women and this has resulted in endemic land underutilisation and low agricultural productivity (Akinola, 2018). In addition to drafting of laws to allow for gender equality with regards to land rights, there is need to change traditional belief systems in SSA (Akinola, 2018). Changing traditional belief systems can be achieved through education and awareness raising, especially among the youth. The most complex constraint to the achievement of land and property rights for women is the cultural one (Akinola, 2018). Men need to be receptive to the change in gender relations and they need to view women as partners (Akinola, 2018). Strengthening women's land tenure security will contribute to human rights and at least six SDGs: goals 1 (no poverty); 2 (zero hunger); 5 (gender equality and empowering women and girls); 11 (sustainable cities and communities); 15 (life on land); and 16 (peace and justice and strong institutions). Chigbu and Enemark (2022) concur, stating that sustainable development cannot be achieved without ensuring that women, globally, have equal rights and opportunities to access and enjoy the benefits of land resources. Achieving gender objectives (e.g. gender equity and gender equality in natural resource use and land tenure) by 2030 requires action to eliminate the root causes of discrimination that still prevent women's access to land and the enjoyment of land rights Chigbu and Enemark, 2022). Making gender vision of development will be largely determined by how land and natural resources are governed at the three levels of government– national, sub-national and local levels (Chigbu and Enemark, 2022). Non-governmental and civil society organizations play an important role in advocating for women's land rights and they will continue to be crucial in the fight for gender equality and in ensuring that women's voices are heard.

Gender and food

Women play an important role in food production, food distribution, and food utilization (Habtezion Z., 2012). They also participate in a range of community-level activities that support agricultural development, for example, soil and water conservation, afforestation and crop domestication (Habtezion Z., 2012). Traditionally, within the household, women play a critical role in securing food for their families (Hyder et al., 2005). They tend to shop for food and/or grow it in their gardens (Ben-Ari, 2014). Women produce up to 80% of food for household consumption and sale in local markets (Ben-Ari, 2014). Agriculture is central to women's livelihoods, however, they encounter several barriers in accessing productive resources, assets, services, and markets (FAO, 2011; Habtezion Z., 2012; Jong et al., 2013; Sakho-Jimbira and Hathie, 2020). They tend to work on smaller farms, have access to fewer livestock and have a greater overall workload which includes low-productivity activities such as collecting water and fuelwood (FAO, 2011; Jong et al., 2013). In addition, women have less access to education, agricultural information and extension services, technology, credit and other financial services (Hyder et al., 2005; Jong et al., 2013). They are also less likely to use modern technological inputs such as improved seeds, fertilizers, pest control measures, irrigation, time-saving equipment, and mechanical tools (FAO, 2011; Meinzen-Dick et al., 2012; Rodgers and Akram-Lodhi, 2019). These barriers make it difficult to participate effectively in agricultural production, increasing their vulnerability to food and nutrition insecurity (Habtezion Z., 2012), and negatively impacting their income generation opportunities (Sakho-Jimbira and Hathie, 2020). This is one of the major reasons why the agriculture sector is underperforming in SSA-women do not have access to the resources and opportunities they need to "make the most productive use of their time" (FAO, 2011, p. 3; Bjornlund et al., 2020). Furthermore, they lack a voice in management decisions- decisions affecting their lifestyles and livelihoods (Hyder et al., 2005; Ben-Ari, 2014).

Sixty percent of the population in SSA population are smallholder farmers (Sakho-Jimbira and Hathie, 2020), and women make up at least 40% of the agricultural labor force

(Palacios-Lopez et al., 2017). However, the contribution of women to agriculture in SSA is often not formally recognized and they face obstacles to engaging on equitable and fair terms (Villamor et al., 2020). The productivity and success of women in agriculture hinges on the availability of land and water- resources in which their access is limited. This limited access means that they achieve lower yields even though they are equally good at farming as men (FAO, 2011; Meinzen-Dick et al., 2012). Studies have shown that if women farmers had the same level of access to resources as men, they can achieve the same yield levels (FAO, 2011). It is estimated that the yield gap between men and women ranges between 20 and 30 percent and the gap is largely due to differences in resource use (FAO, 2011). Transforming gender relations in agriculture by allowing women to have the same access to resources as men and empowering them as decision-makers will have multiplier effects on production, productivity, efficiency, inclusive growth and poverty reduction in the region (Farnworth et al., 2013; Ben-Ari, 2014; Sakho-Jimbira and Hathie, 2020). Rodgers and Akram-Lodhi (2019) concur, stating that closing the gender gap in SSA has the potential to increase crop production by up to 19%, boost agriculture and overall GDP, while lifting thousands of people out of poverty.

Developing and implementing gender-sensitive agricultural and nutrition policies can bring attention to women as key actors of food and nutrition security, while addressing the challenge of feeding an increasing population (Sakho-Jimbira and Hathie, 2020). The transformation should include gender-responsive budgeting, which will ensure that commitments to women's equality are translated into measures to help finance equity measures in the agricultural sector (Farnworth et al., 2013). In addition to increasing women's agricultural productivity, it is necessary to invest in women's entrepreneurship and technical skills, their participation in niche markets, and higher value-added activities (Sakho-Jimbira and Hathie, 2020). It will also be beneficial to explore the complex interactions that exist between gender and agriculture within the sub-Saharan African farming systems in order to have a better understanding of them (Meinzen-Dick et al., 2012). One way this can be achieved is through investing in women's involvement in agricultural research (Sakho-Jimbira and Hathie, 2020). This will allow for perspectives and insights that are more gender-sensitive which can assist to overcome the challenges female farmers are facing on the ground (Sakho-Jimbira and Hathie, 2020). The number of women undertaking in agricultural research in SSA has so far increased by 24%, from <9,000 in the year 2000 to more than 15,000 in 2014 (Sakho-Jimbira and Hathie, 2020). This is likely due to increased access to education for girls, which has resulted in more women enrolling into agricultural sciences, and sciences (MacNeil, 2017).

WELF nexus, gender, and climate change: Interlinkages

Water, energy, land and food resources are important to the livelihoods of women, however, a gender gap exists in all sectors which limits their productivity and their ability to contribute toward wider social and economic development goals (FAO, 2011; Njuki, 2021). Moreover, gender is missing from the WELF nexus frameworks (Villamor et al., 2020). Attempts by the individual sectors to address the gap have not been successful due to numerous factors including political will, budgetary constraints, and the unwillingness of men to change their mindsets (Thuo et al., 2017). Moreover, resource management and allocation in sub-Saharan Africa is conducted using a silo approach which is contributing to the region's failure to meet its development targets, exacerbating its vulnerabilities, and leading to inequitable access to resources (Nhamo et al., 2018). This lack of coordination of WELF nexus synergies and trade-offs in planning is compromising gender equality and the sustainability of development initiatives (Nhamo et al., 2018).

The security of water, energy, land and food resources is critical for the WELF nexus, and this goes beyond resource access (Villamor et al., 2020). It includes the capacity to utilize these resources, and the dynamics and power relationships that affect the management of these resources (G. Villamor et al., 2020). Villamor et al. (2020) found that four aspects differentiate male and female perspectives with regards to WELF nexus resources and these differences include: (i) access to external actors; (ii) perceptions of target resources; (iii) gender specific productive roles; and (iv) decision-making with respect to target resource management and utilization, which may influence the dynamics and governance of the nexus. Overlooking these differences may make it difficult for the nexus approach to achieve gender equity while further aggravating the already burdening roles of women and children within households (Villamor et al., 2020). Resource inequality and access contribute to social instability and insecurity, therefore, incorporating gender perspectives into the nexus concept might help to identify specific local factors that may determine the degree of resource security and sustainable management (Villamor et al., 2020).

Climate change is having a negative impact and increasing pressure on WELF resources in SSA (Nhamo et al., 2018). All four sectors are highly vulnerable to climate change impacts and they also contribute heavily to that change through their greenhouse gas (GHG) emissions (Rasul and Sharma, 2016). Therefore climate change adaptation is intrinsically linked to these sectors (Rasul and Sharma, 2016). Water resources will be the hardest hit by climate change and these impacts are projected to increase in the future (Nhamo et al., 2018). The impacts include high temperatures, especially in the inland tropics, increased rainfall variability, increasing aridity, and increased frequency and intensity of droughts, floods, and extreme heat events (Serdeczny et al., 2017; Nhamo et al., 2018), which are affecting food production and energy generation. Sub-Saharan Africa is said to be the most vulnerable region to the impacts of global climate change because of its reliance on natural resources and agriculture, in particular, rain-fed agriculture, which is highly sensitive to weather and climate variables, and its low capacity to adapt, due to the high levels of relative poverty in the region (Kotir, 2011; Serdeczny et al., 2017). Thus, any negative effect of climate on the water cycle can threaten agriculture production, livelihoods and economy (Kotir, 2011; Nhamo et al., 2018). These challenges are exacerbated by population increase and industrial growth (Nhamo et al., 2018). A large proportion of SSA's population depends on agriculture and as the risk to agricultural livelihoods increases, so will the rate of rural–urban migration, adding to the challenges of urbanization in the region (Serdeczny et al., 2017).

The impacts of climate change are not gender neutral nor are the adaptation strategies (Habtezion S., 2012; Sultana, 2018). Climate change-induced ecological and hydrological changes compound gender disparities in income, health, and education by exacerbating existing development challenges (Sultana, 2018). Men and women tend to have different coping and adaptive capacities and these translate to gender-differentiated vulnerabilities (Habtezion S., 2012). The productive and reproductive roles of women within the household make them increasingly vulnerable to climate change impacts, especially in rural areas as they are responsible for providing food for their households and procuring fuelwood for cooking and drinking water (Villamor et al., 2020). The gendered social roles and gender-based inequalities in access to assets are the primary reasons for the differences in adaptive capacities between men and women (Habtezion S., 2012). Moreover, legal and sociocultural barriers also affect women's capacity to respond effectively to climatic risk (Habtezion S., 2012). Despite its gender neutrality, the WELF nexus presents an opportunity for a coordinated resource management (Nhamo et al., 2018) which will allow for a more equitable distribution of resources and the reduction of vulnerabilities, and the promotion of gender equality.

National and local policies relating to water, energy, land, food security/agriculture, and climate change within SSA need to acknowledge the importance of gender to the WELF nexus and climate change response. In order to advance climate-resilient strategies in the areas related to water, energy, land, and food, the incorporation of gender is crucial, especially for gender equality and operational effectiveness (Thuo et al., 2017). Gender-responsive planning for the WELF nexus will need to acknowledge and address power differentials among men and women within the sectors (Thuo et al., 2017). In mainstreaming gender into the nexus, the different roles of women and men need to be taken into account, and they need to be involved in policy and decision-making processes (Thuo et al., 2017; Sultana, 2018). It is also important to create outcomes that support both functional and strategic gender needs (Thuo et al., 2017). Sultana (2018) notes that while some programmes may address practical gender needs, they fail to address strategic gender needs and systemic gender inequalities, power structures, and exclusions. As a result, masculine bias remains in access to information, employment opportunities, decision-making processes, and institution building (Sultana, 2018).

Capacity needs to be developed for the integration of gender into integrated WELF planning and policies, and gender-responsive planning; funds need to be allocated; and there needs to be political will (Thuo et al., 2017). Care should be taken to not paint women and children as weak and vulnerable but they need to be viewed as actors who have agency and can make significant contributions to decision-making (Thuo et al., 2017). Moreover, it should be acknowledged that despite the increasing awareness on gender relations, cultural biases may affect any progress being made to address gender gaps in planning (Thuo et al., 2017). These biases may also affect the manner in which women participate, adding to barriers in planning and decision-making processes (Thuo et al., 2017).

Following the integration of gender into WELF Nexus and climate resilient planning, there needs to be monitoring and evaluation of progress. Clear indicators of what policy-makers are hoping to achieve need to be developed, as well as transparent processes of how these goals will be met (Thuo et al., 2017). Gendered knowledge about water, energy, land and food production can bolster adaptation programmes in different localities, however, these knowledge systems are often not engaged and individuals or groups do not fully participate in decision-making (Sultana, 2018). Gender inequality and the lack of involvement of differently located women in public decision also compromises the effectiveness of adaptation programmes (Sultana, 2018). The aim of these programmes is to reduce vulnerability to both climatic and non-climatic changes (Rasul and Sharma, 2016), and this is closely linked to achieving the sustainable use and management of water, energy, land and food resources, which are important for water, energy, and food security, as well as sustainable development (Rasul and Sharma, 2016).

Some projects have been launched in SSA to promote women's access to-, and utilization of WELF resources. For example, in Benin, a pilot irrigation project was launched in 2007 by Stanford's Woods Institute for the Environment, in partnership with Solar Electric Light Fund (SELF) (GWP SA, 2019). The project installed three solar-powered drip irrigation systems in two arid rural villages in Benin's Kalalé district, Dunkassa and Bessassi (Eaton, 2012; GWP SA, 2019) to provide a cost-effective and environmentally friendly way to pump water for irrigation from nearby rivers and underground aquifers (UNFCCC, 2016). The project supplies local women's cooperatives with water to grow fresh vegetables for consumption and sale, all year-round (Eaton, 2012; UNFCCC, 2016). These vegetables include tomatoes, okra, peppers, eggplants, amaranth, and carrots (GWP SA, 2019). The women in the co-operatives share the maintenance costs of the new irrigation technology (GWP SA, 2019). In addition to supplying water, the irrigation system freed women from the responsibility of having to fetch water to grow vegetables, especially during the 6-month dry season (GWP SA, 2019), allowing them to partake in educational and economic activities (Eaton, 2012). As a result, women are also empowered to become entrepreneurs and leaders in their communities (UNFCCC, 2016), while implementing solutions that promote food and nutrition, and climate change mitigation and adaptation. The initiative illustrates the role that renewable energy can play in creating new economic opportunities, while bringing water and food to poor communities, and it can be replicated, globally, especially in SSA (GWP SA, 2019; UNFCCC, 2016).

Conclusion

Access to water, energy and food resources is highly gendered in sub-Saharan Africa, especially in rural areas, and women face numerous socio-cultural, economic, legal, and institutional barriers in accessing them, despite their productive and reproductive roles in the household. These resources are crucial for food security and human existence and how they are governed affects outcomes in terms of social equity, externalities, and socio-ecological resilience (Albrecht et al., 2018). The failure of women to access these resources makes them vulnerable, leaving them with a limited capacity to respond to the impacts of climate change, and a limited ability to harness opportunities arising from it. Although some countries in the region have made attempts to incorporate gender equality into their respective policies and eliminate gender discrimination, the implementation of these policies has been fraught with numerous challenges, including the micro-level dynamics within communities and households (Sultana, 2018), which add to the complexity of the challenges. Therefore, any efforts to address gender inequalities with regards to resource access need to address strategic gender needs and systemic gender inequalities, power structures, and exclusions (Sultana, 2018), while defeminizing resource inequality.

Given the interlinkages that exist between water, land, energy, and food, and the fact that access to these resources is gendered, gender needs to be mainstreamed into discussions about the WELF nexus. Adopting the nexus approach to resource management provides governments with an opportunity to create an enabling environment to improve equity in natural resource access; improve resources use efficiency; and abandon silo thinking within the different sectors (Ringler et al., 2013), while contributing climate change adaptation, and multiple goals of sustainable development. This can be achieved by the active involvement of both men and women in decision-making about these resources, and climate change response is crucial to the success to any plans or programmes that are developed and implemented to address these challenges. Furthermore, gender relations need to be transformed and men need to be receptive to the change, and view women as partners. Transforming gender relations by allowing women to have the same access to resources as men and empowering them as decision-makers will have multiplier effects on production, productivity, efficiency, inclusive growth and poverty reduction in the region (Farnworth et al., 2013; Ben-Ari, 2014; Sakho-Jimbira and Hathie, 2020). It is also important to implement effective monitoring and reporting mechanisms in order to track progress systematically (Ghebru, 2019).

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SH conceptualized and wrote the paper. The author contributed to the article and approved the submitted version.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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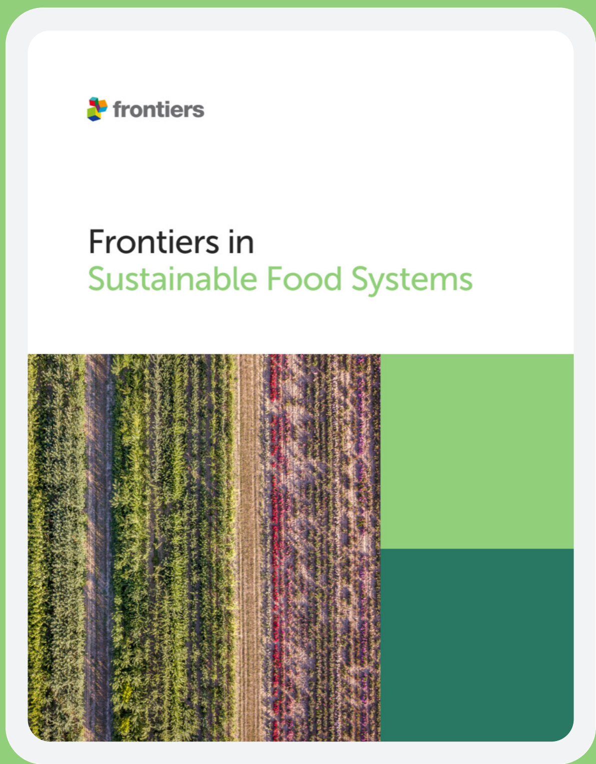

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