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Cross-cutting issues in the water, land, energy and food security nexus: Perspectives from sub-saharan africa

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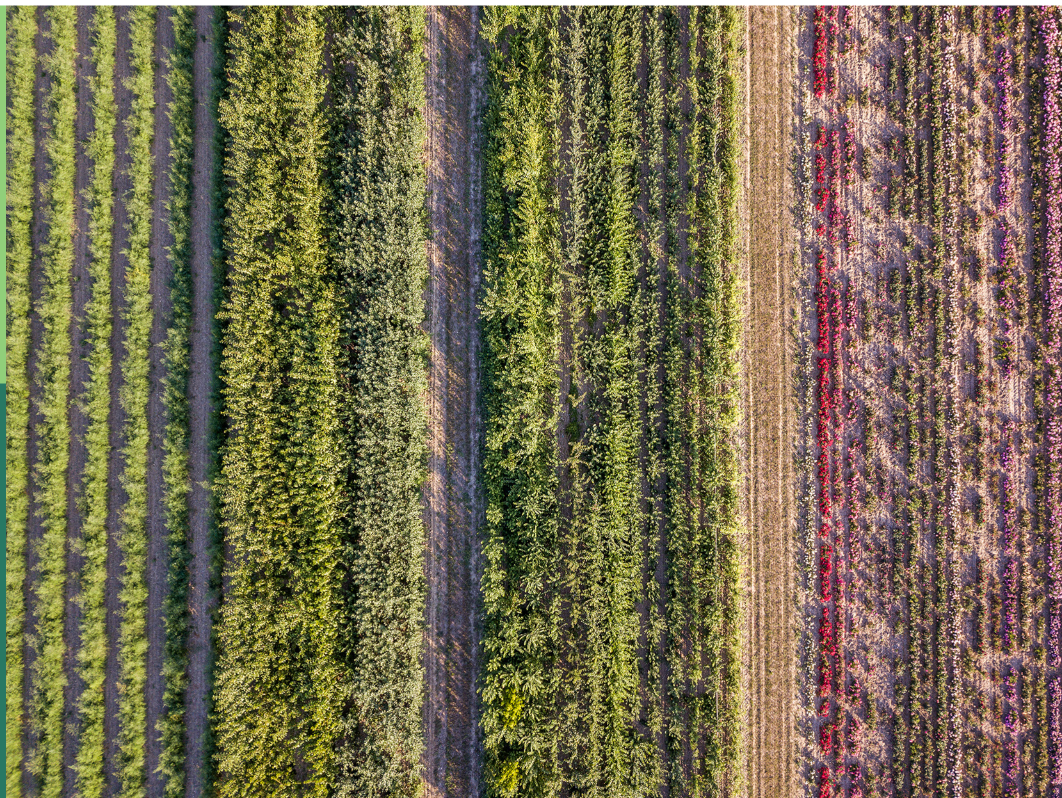

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Cross-cutting issues in the water, land, energy and food security nexus: Perspectives from sub-saharan africa

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Editorial: Cross-cutting issues in the water, land, energy and food security nexus: Perspectives from Sub-Saharan Africa

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Editorial on the Research Topic
Cross-cutting issues in the water, land, energy and food security nexus: Perspectives from Sub-Saharan Africa

Water, energy, and food are crucial elements for human survival and wellbeing. Nevertheless, they are under increasing pressures owing to escalating population coupled with climatic change (Donkor). The intricately intertwined nature of these resources is such that, with progress in one domain comes implications for the others, which calls for a concerted balance for socioeconomic and environmental sustainability. Hence, the escalating pressures and competing interests associated with the food-water-energy nexus necessitates enhancement of governance and management approaches for sustainable socio-economic development (Nhamo et al., 2018). Moreover, these resources are the worst affected by climate change, and offer a space for addressing issues of adaptation, climate system, human society, and the environment. Harnessing the opportunities in this nexus will be helpful for the goal of sustainability and social resilience. However, despite the acknowledgment that energy, agriculture, and natural ecosystems display widespread interlinkages, the fragmented interventions toward attaining resource security compromise sustainability and security in the other domain (s). It is notable that the silo approach results in shortcomings as problem-solving in a domain tends to cause loopholes, becoming more vulnerable by exacerbating risk in another domain (Mabhaudhi et al., 2019). Addressing the cross-cutting issues in the nexus helps harness linkages, synergies, and trade-offs for tailored measures, enhance resource efficiency, and limit impacts and risks in developing the resources. This includes exploring possible trade-offs and synergies, coupled with tailored and/or viable response measures across different sectors. Furthermore, prioritizing cross-cutting issues is vital for promoting social nexus issues, including women empowerment, climate justice, poverty alleviation, and conserving the rights of socially a d economically vulnerable groups.

The intricate interlinkages between water, energy, and food resources coupled with their crucial impacts on socioeconomic development, healthy ecosystems, human development, and sustainable development (Urbinatti et al., 2020), enabled the water–energy–food (WEF) nexus concept to gain traction after the United Nations General Assembly of September 2015. Several countries, including those of the authors of this special issue, have introduced diverse measures and are at different stages of implementation of the concept. Wudil et al. (2023) situate their study of food security at the household level to explore determinants vital for reinforcing food security. Together with Raphela and Pillay, these authors highlight the need for food security interventions to be more multi-dimensional such that they facilitate the social, institutional and economic transformation of small scale farmers. This complements the argument of Oduniyi and Tekana who emphasize that information acquisition is an enabler to the adoption of sustainable land management practices (SLMP). The knowledge attained from accessing to information amongst farmers will equip farmers to better prioritize investment in adaptation and mitigation approaches, including climate smart agriculture, to reinforce resilience (Chitakira and Ngcobo; Obirikorang et al.). The importance of governance in the dynamics of the water-energy nexus cannot be overemphasized. Ultimately, steering the nexus toward sustainability pathways requires effective governance (Naude) that is resilient and inclusive as well (Vidal et al.; Imoro et al.).

The results of this issue have underscored the essence of the concept in foregrounding the interconnectedness of resources and informing policy coherence toward sustainable development. Ultimately, the water-energy-food nexus and the inter-linkages amongst the three resource domains, coupled with the underlying synergies, conflicts and trade-offs require sustainable management. Although the essence of the WEF nexus concept is globally acknowledged as demonstrated by its integration into policy and legislative instruments, its operationalization leaves much to be desired. For example, the findings from the articles in this Research Topic show that its adoption is approached from diverse angles from one country to the other. This can be attributed to differing factors owing to differing geopolitical factors including environmental, the priority attached to it, and socio-economic issues (Nhamo et al., 2020). It is noteworthy that the African Union's Agenda 2063 (The Africa We Want), which serves as the continent's blueprint and master plan, aims to transform Africa into the powerhouse premised on inclusive and sustainable development amongst others. The Agenda 2063 strategic framework on sustainable development relates very much with the United Nations sustainable development goals. Both the Agenda 2063 and the SDGs acknowledge the vital role of the WEF resources in supporting social and economic wellbeing. However, the rising inequality and poverty traps of the vulnerable on the continent further exacerbate water, food, and energy insecurity (Ebhuoma et al., 2020; Tantoh et al., 2021). Moreover, exploiting these resources excessively for food production, energy provision, and water provision results in widespread pollution, deforestation and degradation in many areas of the continent. The need for integrated planning for the continent to overcome these challenges cannot be overemphasized as the final decade of action to deliver the SDGs gains momentum. Governments on the continent will therefore need to give focus to cross-sectoral coordination to overcome fragmented implementation of interventions, which further dissipates resources and compromises regional resilience. The SDG 17 seeks to reinforce implementation measures and strengthen partnerships toward attaining global sustainable development. Such partnerships are crucial to the exchange of ideas, successes and best practices in policy formulation and implementation of the nexus concept. In this regard, there is opportunity to learn from successful case studies on combining multiple policies and tailored measures regarding the water-energy-food nexus (Oduniyi and Tekana). This will help in overcoming the pervasive vagueness, confusion and lack of policy direction in principle and operationalization of the nexus concept. This is more so as this study's findings highlight the lack of cross-sectoral linkages and pervasive silos policy formulation and implementation approach (Imoro et al.). Moreover, the dearth of understanding on the linkages between water-energy-food resources causes concentration on achieving unique goals in a sphere rather than realizing collective and integrated nexus goals. Going forward it is important to enhance awareness, build institutional capacity, increase investment, and strengthen political will toward activities of the WEF nexus. There is also the n d to enhance multi-stakeholder and multi-sectoral platforms toward increased dialogue and evidence-based decision-making regarding the nexus.

Author contributions

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

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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Resilient Governance Regimes That Support Urban Agriculture in Sub-Saharan Cities: Learning From Local Challenges

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Local governments in Sub-Saharan Africa face the daunting task of high urban growth and potentially devastating impacts of climate change across local communities and the economy. Urban and peri-urban food production can be among nature-based strategies planned for improving urban food security, reducing emissions, and climate adaptation. Co-operative governance, strategic planning, and accountable institutions are needed to support urban agriculture (UA), in the face of climate risks, unplanned urban development, the gendered nature of food provision, and the inability of urban farmers to self-organize toward optimal market and land access outcomes. Using a case study approach guided by qualitative content analysis with information derived from web analysis, we apply the Institutional Analysis and Development Framework to analyze underlying governance factors for UA in three selected Sub-Saharan African cities. Our three case cities of Kampala, Tamale and Cape Town reveal that UA is beginning to receive policy attention toward food security, and recognition for generating environmental, ecological, health, and human well-being benefits. Literature from specific cities however does not yet signal a local awareness and policy thrust regarding the associated and pertinent climate adaptation benefits of urban agriculture. We therefore recommend trans-disciplinary, locally-led, planning-based, and multi-sectoral approaches, involving a range of stakeholders toward recognizing and achieving the climate adaptation, environmental (ecologically restorative) and food security benefits of pursuing urban agriculture. This signals a larger role for the practice in sustainability discourse and SDGs 2 and 11, scaling out and up across large, medium and small towns, and cities of Sub-Saharan Africa.

Keywords: collaborative governance, land use planning, Sub-Saharan Africa, urban agriculture, climate change adaptation, food security

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INTRODUCTION

It is estimated that the urban population in Africa will increase from 650 million to more than 1.3 billion by 2050 (UN-DESA, 2019). For local governments in Sub-Saharan Africa, this implies managing the highest urban growth rate in the world while confronting the devastating effects of climate change cutting across local communities and the economy (UN-DESA, 2019; Global Clearing House for Development Finance, 2020).

The IPCC special report on Land and Climate Change states that urban and peri-urban food production can be among the strategies planned to improve food security, reduce GHG emissions, and prepare, respond and recover from the adverse effects of climate change in cities (Mbow et al., 2019). Urban agriculture (UA) fosters local adaptation through e.g., temperature regulation (Tsilini et al., 2015), biodiversity conservation (Lwasa et al., 2011), strengthening of ecosystem services (Lin et al., 2015) and improving urban food security (Lwasa et al., 2011; Davies et al., 2020; FAO, 2020). But urban and peri-urban agriculture is exposed to climate-related risk and increasing pressure over land due to population dynamics. Such factors and processes can hinder the potential of UA to provide broader benefits to society (Padgham et al., 2015).

Food insecurity increases the vulnerability of marginalized groups, such as low-income urban households, as it is experienced alongside multiple, interconnected deprivations such as poverty, health issues, low income, inadequate housing, insecure tenure and income, and climate vulnerability (Baharoglu and Kessides, 2001; Tacoli, 2013). Amidst the Covid-19 pandemic, FAO (2020) points to the relevance of urban food production as a way to achieve greater self-sufficiency. It also highlights the role of UA as a main strategy for urban food production and calls for the preservation of existing agricultural land in urban and peri-urban areas.

In the past years, UA has gained increasing attention, reflected in a growing body of literature on the topic. Unsurprisingly, the majority of publications focus on the analysis and discourse around UA and its role in addressing food insecurity. Few studies, however, look at the specificities of governance and institutions shaping the way UA is conducted (Crush and Frayne, 2014; Frayne et al., 2016; Shannon et al., 2020).

The main objective of this study is to create a deeper understanding of the governance factors that frame the implementation of urban agriculture initiatives in Sub-Saharan Africa as well as their impact on reducing vulnerabilities, such as food insecurity, and increasing resilience to shocks and crises. To do this, Section Introduction presents literature-based information on UA in Sub-Saharan Africa in relation to food security and climate resilience. It also provides a summary of the UA governance frameworks and related challenges. In Section Literature Review the application of the IAD framework in our methodology is explained. Section Methodology and Results analyze UA's underlying governance factors by looking at three selected Sub-Saharan African cities.

LITERATURE REVIEW

Urban Food Security and Climate-Related Risk

Many urban dwellers in low- and middle-income countries face food and nutrition insecurity (Revi et al., 2017). Rather than a general shortage of food, this is mainly explained by low incomes (Cohen and Garrett, 2010; Prain et al., 2010; Crush et al., 2012; Siegner et al., 2018). Low-income urban households allocate more than 50% of their total expenditures to food (Gbadegesin and Olajiire-Ajayi, 2020). This high food expenditure makes them vulnerable vis-à-vis long-term risks such as steady increases in food prices or short-term spikes associated with climatic disasters (Cohen and Garrett, 2010).

The climate-related risk associated with floods, drought, or other extreme events can lead to spikes in food prices in cities (Bartlett, 2008) linked to interruptions or disruptions of food supplies. To cope with increased food prices, low-income households may adopt different strategies, including changing their consumption habits, eating less, often low-nutritious food, or increasing their working hours to generate more income (Cohen and Garrett, 2010). Many of these strategies negatively impact the health of household members, especially the ones that are most vulnerable, such as women, the elderly and children.

The increasing number and concentration of people in cities often place food security in direct competition with other water and land demands, such as drinking water supply and bio-fuel production (Wilby and Keenan, 2012). Climate change is expected to intensify such conflicts as it may create new patterns of climate-related impacts, exposure and vulnerability (Douglas et al., 2008; UNISDR, 2009, 2011).

Urban Agriculture for Food Security and Climate Resilience

Urban agriculture (UA) has been defined by Davies et al. (2020) as "the growing of crops and raising small livestock on land within the urban boundaries of cities and towns (e.g., home gardens, vacant lots, roadsides, and balconies) for household consumption or sale in urban markets." Less than 12 years ago, about 14% of the world's population was nourished by food produced in urban and peri-urban areas (Kriewald et al., 2019). Nowadays, UA continues to be a prominent food source, especially for middle and low-income families (Gbadegesin and Olajiire-Ajayi, 2020).

Besides its valuable contribution to food security, UA can also contribute to the wellbeing of citizens and societies (Battersby and Marshak, 2013; Olivier, 2019), improving biodiversity, strengthening associated ecosystem services (Lin et al., 2015), reducing GHG emissions, and adapting to climate change impacts (Mbow et al., 2019). UA is by consequence tackling the achievement of several Sustainable Development Goals (SDGs), but especially those linked to no poverty (SDG 1); zero hunger (SDG 2); sustainable cities and communities (SDG 11) and climate action (SDG 13).

A review on Sub-Saharan Africa (Lwasa et al., 2014, 2015) shows that UA contributes to climate change adaptation in the cities by lowering the heat island effect, increasing water infiltration, and reducing run-offs associated with flooding (Lwasa et al., 2014, 2015; Kumar et al., 2017). A scenario analysis (Tsilini et al., 2015) also reveals the potential of urban green areas to reduce the surface temperature up to 10°C compared to similar areas without vegetation cover.

Despite the benefits listed above, UA has been criticized for its marginal contribution to food security in lower-income urban households (White and Hamm, 2014), particularly in African urban centers (Crush et al., 2011; Frayne et al., 2016). For example, a study by Davies et al. (2020) found that UA only contributes marginally to household's food security in secondary and tertiary urban areas in Zambia and Kenia. Urban food systems may also bring about negative social and environmental effects, such as lower productivity and inadequate food supply as compared with modern large-scale agriculture (Smith et al., 2019), land use and water conflicts, and contamination of water sources (Gyasi et al., 2014; Bellwood-Howard et al., 2018; Ayambire, 2019).

However, the authors clearly state that UA can still play a significant role in the food and nutritional security strategies, given that other elements are considered. Such elements include making the food supply chain more efficient, improving conditions for farmers' markets, and financing infrastructure and production technologies (Cohen and Garrett, 2010). Further recommendations include fostering innovation to embrace alternative food sources and technologies (e.g., vertical farming), improving supply chains, enhancing of local social safety nets, among others (Weldegebriel and Prowse, 2013; Eakin et al., 2014; Lemos et al., 2016; Schwan and Yu, 2018).

Governance Frameworks for Urban Agriculture and Food Security

There is an increasing agreement on the importance of urban food systems, and consequently, increasing attention is placed on their governance and sustainability (Siegner et al., 2018). A global analysis conducted by Filippini et al. (2019) revealed that cities are developing urban food policies and measures that are being incorporated into cities' policy agendas to increase food security. Such initiatives may be driven by local actors and grass-root organizations or have a top-down approach. The same study shows that many of these initiatives are still early in their development as they have emerged in response to new challenges experienced in urban centers. Some cities, mostly from the Global North, successfully developed, and implemented comprehensive policies on urban food security. Contrary, policies in other cities are still on early development or actions were taken place in a disarticulated manner with low participation of relevant actors.

Urban food security requires integrated governance and the articulated work of institutions and stakeholders across a wide range of economic sectors such as agriculture, environment, health, and education (Mbow et al., 2019). But the governance of urban food security is challenging as it often lacks clear regulations. It falls within the responsibility of a range of government actors, many of which may have low implementation and control capacities and, in some cases, conflicting interests (Smits, 2018).

The informality that characterizes many cities in Sub-Saharan Africa, adds an additional layer to the urban governance challenges. By 2050, the population living in informal conditions will likely triple to about three billion (Satterthwaite et al., 2018). Such a growing population has coped with the absence of formal services by developing their own economic dynamics, which has been argued to be low-carbon and resource-efficient (see Brown and McGranahan, 2016). However, urban agriculture is still not part of most statistics, mainly because agricultural data is usually not disaggregated into urban and rural. As such, its contribution to the urban formal and informal economy remains underreported (Brown and McGranahan, 2016).

METHODOLOGY

This study uses a case study approach which is guided by qualitative content analysis, with information derived from web analysis. The selected case studies are analyzed using the Institutional Analysis and Development (IAD) framework to policy analysis and design proposed by Ostrom and Polski (1999) and Polski and Ostrom (n.d.).

Case Study Selection

Information on the case studies was collected through desk-based research based on literature review and policy analysis. An important criterion for the selection of case studies was the availability and extent of the information related to UA in a given country. A search on google scholar using the terms "Urban Agriculture" per Sub-Saharan African country was performed. The 10 countries with the highest number of publications since 2017 were further looked into. These included South Africa (4900), Kenya (4650), Nigeria (4200), Ghana (3740), Ethiopia (3400), Tanzania (2900), Uganda (2460), Malawi (1340), Cameroon (1220), and Sudan (1110). For those countries, a further web search was done in order to identify specific case studies of interest.

The final identification of cities was made considering the following criteria (1) UA as a widespread practice; (2) extend and information on UA available from the literature, especially in relation to governance factors; (3) geographical dispersion to provide a wider perspective of the different institutional arrangements in Sub-Saharan Africa. Even though there is an increasing body of literature on UA, few cities were eligible for our analysis due to the limited and incomplete information available on the institutional characteristics shaping UA in cities. The selected case studies were Tamale (Ghana), Kampala (Uganda) and Cape Town (South Africa). The general description of these cities and the characteristics of UA can be found in **Appendix A**.

For each case study, all relevant information found *via* web search, including scientific and gray publications as well as official documents, were considered to form a picture of the different elements shaping the governance around UA. The specific documents used for the analysis are cited accordingly in this document.

Case Study Analysis

The IAD framework is a tool that allows to analyze policy interventions implemented in a wide range of complex political-economic situations as well as to understand how institutions develop (Ostrom, 2011). This framework helps to understand complex social situations by diagnosing important elements of policy processes and breaking them down into manageable sets.

It identifies key elements in decision-making situations within the policy process, known as *action situations*, and the way these are shaped by external variables (Ostrom, 2011). Actors, both individuals and organizations, are the *participants* in an action situation (*Ibid*.). They are influenced by their physical and socio-economic environment as well as laws and regulations (Heikkila and Andersson, 2018). The physical environment in which an action scenario is set is referred to as the *biophysical/material conditions*. The socio-economic features of the community that make up the social environment of the action situation are described by *attributes of community*. The rules represent the formal laws and regulations that facilitate or inhibit participant activity in an action situation's institutional setting (Ostrom, 2005). The outcome of an action situation, together with the interactions of the actors, are evaluated using various criteria determined by the participants and observers in action situations.

For each case study, a first scan of the available literature informed the decision about the Action Situation(s). The only criterium was the recognition of a relevant policy process influencing UA, that is, a process that could enable or hinder UA implementation and its provision of benefits. Once the action situation was recognized, available documents were revised to identify the action situation elements: participants, rules in use, attributes to the community, and biophysical conditions. The outcome of applying the IAD framework was the systematic analysis of a policy process that, in turn, was the basis for developing a narrative around the elements shaping the process, their interaction and outcomes.

RESULTS

In this section, the results of the analysis of the three case studies, using the IAD framework for policy analysis, are presented. The results are summarized in **Table 1**. This encompasses more specifically the unraveling of the physical conditions, attributes, rules-in-use, actions, pattern of interactions, and outcomes around UA and the institutional factors that support or inhibit UA to achieve greater food security in the cities that have been selected.

Case 1: Tamale, Ghana

Land-use conflicts in Tamale have received academic interest and coverage (see Fuseini, 2016; Akaateba, 2018) and so has the topic of urban agriculture. This paper draws from and builds on existing studies to offer an alternative lens to view the complex nexus between formal and informal land systems, spatial development, and their effect on urban agriculture in this city. In the interest of maintaining the focus on this nexus, other aspects and emerging issues regarding urban agriculture in Tamale, such as water access and quality, production technologies and inputs, crop commercialization, and access to markets, have been deliberately not addressed in this study.

Land Tenure and Land-Use System in Tamale

The land-use system in Ghana is a dual one, in which formal or statutory land tenure regulations co-exist with customary tenurial arrangements. The latter is the predominant one, with about 80% of the country's land under customary ownership (Fuseini, 2016). As such, most land is owned and managed by chiefs while the people enjoy only usufruct rights.

According to the land governance in Tamale, one way in which citizens could access land for agriculture is by requesting it to the traditional chiefs. Customarily, chiefs—who are the custodians of most of the land in Tamale city and surroundings—can grant land to a person in exchange for a token or gift. In present times, however, such tokens have been replaced by money. The monetarization of the access to land, together with the growth dynamics regarding infrastructure and service provision, has created pervasive incentives for allocating land to the highest bidder. As is the case, chiefs face strong claims of putting their own interests first and seek for profit before the public interests (Fuseini, 2016; Cabannes and Marocchino, 2018). Not surprisingly, land allocation to farming, which was common in the past, has been marginalized in favor of urbanization (Gyasi et al., 2014; Kuusaana and Eledi, 2015).

A second path through which citizens could access land for agriculture in the city of Tamale is by directly acquiring a permit from the metropolitan authorities. According to the 2016 Ghanian Land Use and Spatial Planning Act (Act 925), urban farming activities are allowed provided that the district, municipal, or metropolitan assemblies issue a permit. In practice though, the city does not have land officially zoned for agriculture, and the metropolitan authorities do not have a specific urban agriculture policy in place. Because of this, agricultural permits are not granted within the city of Tamale (Bellwood-Howard et al., 2015a).

As summarized above, the land governance in Tamale is complex and characterized by a lack of coherency between policy bodies and government units. Adding to this, land market speculation and the apparent corruption of the customary land use authorities generate difficult conditions for urban agriculture. As a consequence, agricultural plots are relegated to the periphery of Tamale, or within the city, to (1) areas around irrigation sources such as gutters, commercial pipes or reservoirs; (2) backyard farms located between houses or (3) individual farm plots on undeveloped building sites (Bellwood-Howard et al., 2015a). As a rule, most of these locations are not land secure; agricultural plots are constantly under threat of invasion by commercial and residential land users, or—in the case of public land—under eviction threats from the management of the public institutions whose land the urban farmers operate (Ayambire, 2019). As an example, Nchanji et al. (2017) reports that Buipela, once one of the largest sites of vegetable production in Tamale, has now almost completely disappeared, with more than 90% of its original area allocated to residential development and the construction of a slaughterhouse. This situation hinders the ability of urban agriculture to deliver benefits to livelihoods and creates significant challenges for the farming livelihoods in Tamale.

Legal Framework

The government of Ghana has set in motion several processes to address the weaknesses of its decentralized land-use system. The main one is the Land Use and Spatial Planning Act (Act 925), drafted in 2011 and passed into law in 2016 (Akaateba, 2018).

TABLE 1 | Results of the analysis of the three case studies; i.e., Tamale, Kampala and Cape Town, using the IAD framework for policy analysis (Ostrom, 2005).

IAD domain	Tamale (Ghana)	Kampala (Uganda)	Cape Town (South Africa)
Timeframe	2011–2020	2005–2021	2011–2020
Focus	Land use policy and Urban agriculture	Transitioning from Informal to Formal Governance Structures	Multi-sector approach to Governing Urban Food Systems
Sources	Bellwood-Howard et al., 2015a, 2018 in Gyasi et al., 2014; Kuusaana and Eledi, 2015; Nchanji et al., 2017; Cabannes and Marocchino, 2018; Edwin et al., 2020	Vermeiren et al., 2013; Sabiiti et al., 2014; Ministry of Land, Housing Urban Development, 2017; Mugisa et al., 2017; Kampala Capital City Authority (KCCA), 2019, 2020; Bidandi and Williams, 2020; Ruhweza, 2020; Mwesigye and Barungi, 2021	Battersby et al., 2011; Battersby and Marshak, 2013; Olivier and Heinecken, 2017; Paganini and Schelchen, 2018; Kanosvamhira, 2019; Crush et al., 2020; Gajjar, 2020; Haysom et al., 2020
Physical conditions	Increasing population (∼about 400,000 inhabitants) *About UA:* - Widely practiced, mainly by women. - Main purpose income generation and food security. - Practiced around water sources and in vacant housing plots all over the city. *Constaints of UA:* - Not recognized as valid urban land use category - Lack of legal framework - Not integrated in urban planning	City has 1.65 million inhabitants, with a rapidly growing population (5.2% annually). *About UA:* - Important source of food and employment - Mainly vegetable production and livestock keeping - Practices: fertilizer, irrigation, food towers, …. - Selling of produce on informal markets, as formal are inefficient. *Constrains of UA:* - Urban growth -> displacement to periphery -> increase transportation cost/time for selling (perishable) goods at central market. - Climate risks (e.g., floods). - Disease, theft, high cost of inputs and poor seed quality. - Waste management. - unawareness of the policies and non-conformity the existing regulations – - Inefficiency of the institution to provide services to the people due to various reasons: insufficient grant from the central government, understaffing of the organization, poor terms, salaries and benefits of the staff	Large population (∼4.6 million) and growing at 2.5% annually. The Philippi Horticultural Area (PHA) has been the breadbasket of Cape Town since historic times. *About UA:* - Practiced in densely populated areas, beyond the inner city - Practiced more by female-headed households - UA supplements food budget and generates income - Cultivation groups use derelict or waste land - Close to 90% of urban farmers use organic agriculture techniques such as compost, liquid manures, crop rotation *Constraints of UA:* - Poor soil quality and severe drought impede urban farming. - Benefits of UA are difficult to quantify, need greater policy attention - Critical deterrents such as land tenure, water access, spatial fragmentation, lack of self-organization - Vulnerability to government-mandated water restrictions
Attributes to community	Less than 47% of Tamale's population is classified as food secure. About UA: - Different discourses regarding land reform, drawing legitimacy from varied sources (history, culture, law). Urban farmers: - Majority subsistence farming for supplementary source of food or income, a small part leisure activity for wealthier class - Farmers perceive secured land based on social relationships of trust rather than legal status. - Perception that formalization of the administration of land rights is a complicated process.	Agriculture has improved nutritional outcome of the urban poor children. There is positive co-relation between household food security and number of livestock units, with improved weight among 2 to 5 years old - 1/3 households involved in UA is female headed. - ∼ 40% of households convert kitchen waste into manure and recycling mainly by higher educated heads. - < 50% of households had training on agricultural topics and member of agricultural association. Urban farmers: - Subsistence: cultivation for survival on wetland and public land, surplus sold. - Garden: cultivation for household, income from other activities. - Commercial: few, owner of land, selling produce.	- 45% households are food secure, 36% were severely food insecure. - Low-income, informal settlements suffer from high levels of food insecurity, especially female-headed households. *Urban farmers:* - Two types of urban gardens co-exist: backyard and market gardens. - A huge diversity among beneficiaries in terms of struggles and cultures, backgrounds, economic status. - UA provides a sense of meaning and empowerment for communities struggling with social ills. Incidents of sabotage and lack of trust do exist. - Around 4,000 backyard and market gardeners in different townships in Cape Town, have been trained by NGOs or the communal extension services to improve market access.
Rules-in-use	Ghana operates a hybrid system of land tenure/ administration: - Formal or statutory: public land used for public purposes (e.g., markets, waste disposal, hospitals) - Customary tenurial arrangements: land which is controlled by a group, clan or family and administered for the benefits of its members as well as those who acquire right of use through laid-down procedures and rules*	Uganda governs at the national and local level. - Uganda has four different type of land tenure system recognized by the Land Act 1998: customary, freehold, leasehold and mailo - Before 2005, urban farming illegal, then ordinance to regulate hygiene and way food produced and sold - Nationally, UA is supported by National Agricultural Advisory Services (NAADs) and Kyanja Agriculture Resource Center	South Africa governs through three interdependent spheres of government at national, provincial and local scales. - Nationally, urban agriculture is considered crucial for poverty alleviation; enabled through the City of Cape Town (2007), which guides the allocation of inputs, resources, training and land for urban farming in the city and the City of Cape Town (2013) aimed at collaboration between various actors (various)

(Continued)

TABLE 1 | Continued

IAD domain	Tamale (Ghana)	Kampala (Uganda)	Cape Town (South Africa)
	- About 80% of the land in Ghana is customarily owned. Public land is acquired from the customary sector.	- City government actively promotes UA increase food security, household income and employment - Competition for land, weak tenure position for many subsistence farmers on institutional and public land - Requirement of permit from council to farm in Kampala (UA is permitted on all land except wetlands, parks and land to be developed).	- More recently, the local governments' agency in achieving sustainable food systems, is recommended through the adoption of Food Sensitive Planning and Urban Design, enabled by planning legislation at all three levels of governance. - An "all of society" approach is recommended by the IUDF, 2016, which guides local governments in achieving sustainability goals through spatial transformation - Land tenure has been cited as a challenge by residents
Action arena	*Action situation* UA is practiced by 44% of households in Tamale and is an important contributor to food security. - The Land Use and Spatial Planning Act (Act 925), drafted in 2011 and passed into law in 2016, aimed to revise and consolidate the laws on land use and spatial planning, provide for sustainable development of land and human settlements through a decentralized planning system [...] and to regulate national, regional, district and local spatial planning. - Between 2011 and 2016, a multistakeholder process to took place. And consolidated into a Multi-Stakeholder Forum (MSF) on urban and peri-urban agriculture. - A main topic within the MSF was the availability of land for urban agriculture and discussions on the informal status of the activity. *Actors:* Farmers and their associations; Local Assemblies; Traditional Chiefs & the traditional land secretariat; Tamale's Metropolitan Assembly incl. its the Town and Country Planning Department (TCPD); NGOs such as the Urban Agriculture Network URBANET and the Resource Center on Urban Agriculture and Food Security (RUAF); the Ministry of Food and Agriculture (MOFA); among others.	*Action situation* UA is practiced by 50% of households in Kampala and is an important contributor to food security. The Kampala City Council legalized urban agriculture enforcing various ordinance to ensure health and quality standard for meat, fish, agriculture, milk and livestock City authority perceive the informal food market as a threat by city authority and are evicted citing lack of proper hygiene to handle food. Urban agriculture unit has been established within Kampala City Council Direct engagement by city authorities in instituting the ordinance *Actors:* Urban farmers; Policy makers (e.g., city authorities); Urban planners; NGOs; Others (e.g., landowners, ...), urban producer association, urban agriculture practitioners: school, health centers, prison, police barracks	*Action situation1:* UA contributes negligibly to food security and income generation in Cape Town (through research) - The motivations for UA are health and ecological reasons. - The main challenges to generate enough for access to formal markets cited by urban farmers were access to markets, access to transport, weak soil health and since 2017, severe water restrictions. - Despite presence of state and non-state actors, actions lack co-ordination toward reaching the economic and health potential of urban farming. *Action situation2:* UA holds the potential for achieving food security and substantial income generation for urban farmers (through practice) - The COVID-19 pandemic triggered higher levels of indigency among the most impoverished and historically disadvantaged communities in South Africa. - Local NGOs stepped up efforts to service urban farmers in their network and to help establish new backyard and community food gardens. - Local NGOs in food production relaunched manure supply runs to small-scale farmers and extended regular mentorship. - With limited government support, the NGOs used digital technology to conduct on-line trainings during lockdown. *Actors:* Farmers networks; Municipal Government; Western Cape department of Agriculture; Department of Economic Development Finance Directorate—property management department; Social Development Dept. —Early Childhood Directorate; Consumers, high-end restaurants; Life-style markets; Research networks—AFSUN, HCP NGOs are significant actors; Early Childhood Centers
Patterns of interaction	- Between 2011 and 2016, the Multi-Stakeholder Forum (MSF) on urban and peri-urban agriculture was formed and active with broad participation of stakeholders. It was led by NGOs and not by local authorities as would have been desirable. - Traditional authorities criticized Tamale's Metropolitan Assembly and the TCPD staff members for being inefficient.	- The role of urban planners and policy makers is considered to have a direct impact on the future of many subsistence farmers with a weak tenure position. - The dominant type of Land Use System is residential development - Locals consider formal food markets, mostly open-air markets as major source of fresh food supply.	- Cultivators from the same area pursue collaborative livelihood strategies to share production costs. - The theory of social capital is invaluable to enable links between farmers and supporting organizations. - NGOs have been the main instigators of UA activities, connecting cultivators to the markets for income generation, and to public institutions to assist in facilitating land access.

(Continued)

TABLE 1 | Continued

IAD domain	Tamale (Ghana)	Kampala (Uganda)	Cape Town (South Africa)
	- Traditional authorities themselves faced allegations of corruption and usurpation of powers of the TCDP, converting farmlands into residential plots for profit and disregarding official planning regulations. - Despite a desire for formalization, farmers may not be whiling/be unable to pay for space in designated agricultural zones.	- Small scale urban farmers struggle to ensure regular and consistent supply to meet the demand of supermarkets - There is increased competition between agriculture land users and non-agriculture land users - Residents are using prohibited land such as road reserves, wetlands, greenbelts etc. for agriculture - Some urban farmers started using rooftop rainwater harvesting to irrigate crops - Kampala city has Agriculture Advisory Service Officer who is in charge of the NAADS programme in the city - Kampala Capital City Authority (KCCA) strategies has been aiming to transform UA from subsistence farming to commercial agriculture.	- Inclusive urban initiatives require information about the collaboration between farmers and supporting organizations. - As a result of the current food and nutrition policies, food production is an unfunded mandate for local governments in SA. - The SPLUMA (Spatial Planning and Land Use Management Act) provides normative spatial development principles for decision-making for all spheres of government: spatial justice, spatial sustainability, efficiency, spatial resilience and good administration.
Outcomes	- The enforcement of Act 925 is ongoing. No impacts of the implementation of Act 925 in the way UA is conducted in Tamale have been reported. - Although informal, urban food production is tolerated and prevails. - The perception of different stakeholders regarding land functions differs (e.g., agriculture, buffer zone, residential) - By 2016, the Tamale stakeholder process identified several areas for policy attention and produced a policy narrative. A local strategic agenda for UA that outlined a common vision for the development of UA in Tamale was developed. - Between 2004 and 2014, a 22.4% decrease in urban area allocated to open space vegetable farming has been reported. As urbanization increases, farmers continue to be pushed unto less favorable sites, peri urban areas or restricted to unauthorized public spaces in order to continue production. *Recommendations:* - Implement the local strategic agenda for urban agriculture. Improve land tenure, establishing more secure ways to access agricultural plots in and around the city of Tamale. - To include UA as part of the Local Plans a mapping of potential production areas within and around the city of Tamale would be a valuable first step. - Implement the above-mentioned recommendations under the leadership of the Tamale Metropolitan Assembly and with wide participation of relevant actors.	- Due to positive contribution of UA to food sufficiency, the city authority is continuously changing its legal and administrative framework conducive to urban agriculture - Urban agriculture well recognized under the Poverty Eradication Action Plan (PEAP) - Ministry of Land, Housing and Urban Development, 2017 proposes UA as one of the strategies for socio economic transformation and development - KCCA ongoing strategy 2020/21-2024/25 has prioritized UA as a strategy under local economic development plan - Rezoning into urban agricultural production zones, namely the core zone, intra-urban and peri-urban zones. - Implementation of the projects like edible landscape project to support UA and strengthen existing ordinance. *Recommendations:* - Protect (peri-)urban land for food production, advantage for organization of mobility/infrastructure and provision of utilities/social services, allow to better cope with climate risks. - Optimize benefit and minimize risk of waste reuse. - Provide food on markets with acceptable quality, price and hygienic conditions. - Providing training on: use of household biodegradable waste; irrigation water management strategies; agronomic and marketing aspects. - Recognition and Investment in informal food market. - Increase of access to infrastructure/assets for UA. - Increase knowledge on agriculture.	- Cape Town boasts a diversified urban agricultural sector with multiple actors, cross state and non-state domains, in addition to farmers. - A difference in the framing of the benefits derived from UA among state officials (economic and food security) and cultivators (social and personal) yields different approaches to UA. *Recommendations* - The economic and health benefits of urban agriculture can be attained by studying, recording and leveraging the networks of existing NGOs, which were active and successful during lockdown. - Local government can unlock its agency in sustainable food systems, by applying the transversal approach of food sensitive urban planning. - Multiple research networks have produced knowledge related to the state and nature of household level food security, social capital and diverse benefits of urban farming, which can inform a multi-sector approach to urban food systems. - The 2017 drought severely restricted food production across backyard and market gardens. This needs policy and planning attention toward improved water security in the region.

This encompasses more specifically the unraveling of the physical conditions, attributes, rules-in-use, actions, pattern of interactions and outcomes around UA and the institutional factors that support or inhibit UA to achieve greater food security in these three cities.

The Act 925 aims to "revise and consolidate the laws on land use and spatial planning, provide for sustainable development of land, and human settlements through a decentralized planning system [...] and to regulate national, regional, district and local spatial planning [...]" [Land Use and Planning Act (2016) (Act 925), 106, 2016].

Act 925 introduced a hierarchical spatial planning model with three levels for the whole country, comprising the development of Spatial Development Frameworks (SDFs), Structure Plans (SPs), and Local Plans (LPs) (Akaateba, 2018). In 2016, stakeholders who participated in the Multi-Stakeholder Forum (MSF) on urban and peri-urban agriculture in Tamale indicated that spatial planning was expected to become more participatory once Act 925 was passed. City planners would be required to consult citizens during the development of the Local Plans, which would open a way to put agriculture on the city development agenda (Bellwood-Howard et al., 2018).

Following Act 925 and the complementary Local Government Act (Act 936), also passed in 2016, the Tamale metropolitan authority—the Metropolitan Assembly -, is legally recognized as the highest political, administrative, planning, and rating authority in its area of jurisdiction.

Through the Town and Country Planning Department (TCPD), the Metropolitan Assembly is the sole authority in charge of preparing and approving Structure and Local Plans, as well as enforcing development control regulations, granting physical development permits, and enacting by-laws. Traditional authorities are expected to engage with the TCPD in the creation of local land-use plans as a result of this constitutional mandate.

While the enforcement of this new formal land use and spatial planning system is still ongoing, most decisions concerning the implementation of the Local Plan are still made by the traditional chiefs, and the implementation of Local Plans remains limited (Akaateba, 2018). The lack of logistical capacities and insufficient training and motivation of the TCPD staff, and the constitutionally guaranteed powers of chiefs over land allocation are some of the reasons behind the low success of the new land use and spatial planning system (*Ibid.*).

Recent literature also questions the success of the new legislation in increasing the involvement of local stakeholders in land use planning. A study by Poku-Boansi (2021) reveals an absence or limited participation of citizens in the land use planning process. He attributes the high incidence of non-compliance to the failure of authorities and city planners to meet the interests of stakeholders. This was already a problem reported by Bellwood-Howard et al. (2018) back in 2016. TCPD authorities manifested a lack of participation during the consultations over land zoning in Tamale, which contributed to the persistence of different perceptions of land by different stakeholders.

Lastly, the predecessor of Act 925, the Local Government Act 426 (1993), was questioned by several authors (see Nchanji et al., 2017; Bellwood-Howard et al., 2018; Nchanji, 2018) for discouraging urban agriculture as it prohibited farming without due permission within settlements of over 5,000 inhabitants. Act 925 has, however, not introduced any changes in this regard.

Stakeholder Participation

Despite the limitations mentioned above and the lack of political attention and legitimacy, numerous stakeholders, notably non-governmental organizations, acknowledge the benefits of urban agriculture (Nchanji et al., 2017). This interest motivated the establishment of a Multi-Stakeholder Forum (MSF) on urban and peri-urban agriculture, driven by the Resource Center on Urban Agriculture and Food Security (RUAF), the Ghana WASH Alliance Programme, University for Development Studies, the International Water Management Institute, the UrbanFoodPlus research project and facilitated by the Urban Agriculture Network URBANET (Bellwood-Howard et al., 2015b).

The MSF has served since 2011 as an intermittent space to discuss issues related to urban agriculture as well as sanitation and waste management. Other stakeholders, including the municipal authorities, research organizations, NGOs, traditional authorities, and representatives of farmers and traders, also participate in this space. Due to the large involvement of different stakeholders, the MSF enjoys legitimacy and has served in the past as a platform to discuss the emerging tensions between urban agriculture and spatial development priorities in Tamale (Bellwood-Howard et al., 2018). In this regard, primary concerns included the diminishing availability of land for agriculture and the lack of formal consideration of agriculture as an urban land use (*Ibid.*).

Bellwood-Howard et al. (2018) documented the different interests and perceptions gathered around the above-mentioned concerns. Among others, the traditional authorities blamed the lack of public spaces for i.e., agricultural production on the TCPD staff, who according to them had failed to acquired enough land from them. On the other hand, TCPD members reported that the traditional authorities continued to allocate land for residential purposes for profit disregarding the law. They also expressed their willingness to initiate participatory land zoning processes. In practice though, such participatory process never materialized. Another important stakeholder, the farmers themselves, were in favor of formalizing urban agriculture but contradictorily, they were not willing or not able to pay for the use of land for production.

Despite the diversity of opinions and interests in urban agriculture represented in the MSF, in 2014 stakeholders of the MSF agreed on a City Strategic Agenda on urban and peri-urban agriculture. This agenda summarizes the joint vision of the stakeholders within the MSF for urban and peri-urban agriculture as a way to "ensure food and nutrition security in a resilient and sustainable city" (Bellwood-Howard et al., 2015a, p.7). The agenda also contains several strategic objectives and actions between 2015 and 2020, including measures to demarcate and register agricultural land and spatial zoning in collaboration with the traditional authorities and the metropolitan authorities (*Ibid.*).

The MSF provided a space to discuss and find solutions to the problems of urban agriculture in a participatory manner. As such, it is a first valuable step toward official recognition of this production system. But the MSF has been criticized for being led and funded by NGOs (Bellwood-Howard et al., 2018). Leadership by public sector actors would legitimize and enhance the sustainability to these participatory processes. The implementation of the City Strategic Agenda on urban and peri-urban agriculture would certainly help legitimize this activity and help mainstream it to the relevant local institutions.

Outcomes and Recommendations

Despite the limitations to access land area and increased eviction pressure, urban agriculture is practiced by about 44% of households in Tamale. It has and continues to play an essential role in food security and income diversification (Bellwood-Howard et al., 2018). The failure of formal governance structures to support urban agriculture has given space for developing a parallel informal framework that is socially accepted and politically tolerated. However, this framework also does not benefit agricultural producers, whose interests are undermined by more powerful players and real estate market dynamics.

Recommendations regarding land tenure include establishing more secure ways to access land for agriculture in and around the city of Tamale. This can be achieved in several ways, including formal mechanisms such as legal title and law enforcement, as well as informal mechanisms such as community legitimacy and rights enforcement (Gyasi et al., 2014).

The first step for this could be the mapping of potential production areas. This mapping exercise could serve as a basis for suggesting zoning areas for agriculture which, in turn, could inform the development of an urban agricultural policy for the city of Tamale (Kuusaana and Eledi, 2015). Ideally, such an initiative would take place under the leadership of the Tamala Metropolitan Assembly (Bellwood-Howard et al., 2015b) with the active participation of other local authorities and community members (Gyasi et al., 2014).

When identifying land for agriculture, areas that deliver ecosystem functions and help reduce climate-related risk should be given priority. In Tamale, this is the case of open spaces, as well as reserve and buffer areas such as valley-bottom lands, which can help mitigate flood risk and make the city more resilient against a potential increase in heavy rainfall with climate change (Gyasi et al., 2014; Fuseini, 2016).

Extreme heat and flooding have a long history in Tamale, with multiple severe events recorded since 1950 (Kayaga et al., 2021). Poor urban governance, particularly inadequate planning and encroachment on waterways, is seen as responsible for the frequent and increasing incidents of flooding in Ghanaian cities (Fuseini, 2016). Besides the well-documented contribution to livelihood diversification and food security, urban agriculture in Tamale also holds the potential to deliver ecosystem services and support climate change adaptation and mitigation (Gyasi et al., 2014; Padgham et al., 2015; Fuseini, 2016). Regrettably, the current structures and general characteristics governing the agricultural production in the city of Tamale hinder its contribution to shaping Tamale into a sustainable and resilient city.

Case 2: Kampala, Uganda

Land Tenure and Land-Use System in Kampala

Uganda has four legally recognized multi-layered land tenure systems: customary, Mailo, freehold, and leasehold (Mwesigye and Barungi, 2021). Mailo land tenure refers to the land given to the Buganda royal family, chief and others to own land as their personal property. Mailo land tenure was created by the 1,900 Buganda Agreement between the colonial government and the Kingdom of Buganda. The dominant system is customary tenure, accounting for 80% of all land, followed by the Mailo system. These two systems have limited land tenure security and land rights. The customary land tenure system is changing from communal to more private land ownership. In the communities where land rights are more privatized, the individual has the full right to sell land without prior approval from a family member or clan head. In contrast, this provision is absent in communities with weak private land rights. Similarly, landlords with complete rights and tenants and occupants with usufruct rights characterize mailo land tenure (*Ibid*). Last, freehold and lease hold land tenure systems both provide more secure land rights than the other systems, but the total land under these categories is negligible.

The random and uncoordinated development caused by lack of qualified planners, weak institutional structures and government policies directly impacts urbanization and urban sprawl (Bidandi and Williams, 2020). Increased competition between agricultural and non-agricultural users has led to the urban poor settling in marginal lands such as wetland areas, exposing them to climatic risks such as flooding. Wetland areas, which are also crucial for regulating flood and filtering sediments, are encroached by new settlers who are farming and producing bricks with clay soil dredged from the wetlands (Sabiiti et al., 2014). The most dominant land use type in Kampala is residential. Sabiiti et al. argue that the explosive growth of the urban population between 1974 to 2008 has contributed to fast-paced land-use changes at the expense of agricultural lands. Vermeiren et al. (2013) projected an increase of the total built-up area from 386 Km^2 in 2010 to 1,000 km^2 by 2030. As such, there is an increasing challenge to acquire land for housing, industries, public infrastructures, and other amenities, causing a negative impact on planning and creating tension between landowners, private persons, urban authorities and the central government.

Legal Framework

The land act 1998 of Uganda recognizes all four above-mentioned land tenure systems, making the act weak in promoting planned urbanization. A large share of the land in Kampala is privately owned (Mailo land) by local people. This poses challenges in promoting planned urbanization since private landowners have full rights over their land (Bidandi and Williams, 2020). The Kampala City Council legalized urban agriculture and enforced various ordinances to ensure health and quality standards for production. The urban agriculture ordinance of 2006 bans urban farmers from practicing urban agriculture without a proper permit and a valid license issued by the Kampalaf Capital City Authority (KCCA). This ordinance also prohibits agriculture on public lands such as road reserves, wetlands, greenbelts, parks, landfills and other areas declared toxic by the city authority. It also prohibits the use of manure that has not been treated. Yet, many subsistence farmers disregard these regulations or are unaware of them (Sabiiti et al., 2014). Institutional and public grounds in Kampala are often used illegally or under informal tenure arrangements for agriculture: a situation that is considered both illegal and unsustainable by the city authorities (Vermeiren et al., 2013).

Stakeholder Participation

Urban agriculture in Kampala is shaped by a rich variety of actors and activities. There are three different typologies of urban farmers: (i) subsistence farmers, who produce food for household consumption and sell remaining food to complement household income, (ii) garden farmers, who have another primary occupation and produce food for self-consumption, and (iii) commercial farmers, who farm at large scale and for whom agriculture is the primary source of income. The majority of urban farmers producing vegetables, poultry and livestock in Kampala are female. Men are primarily engaged in pig and cattle rearing, which involves trading activities.

Kampala has two common food market types: formal and informal ones. Traditional open-air markets are formal and a major source of fresh food in the city. Similarly, supermarkets, also formal markets, are increasingly popular. However, informal food sellers such as stock stores, illegal booths, and street/pavement vendors provide a substantial portion of the produce consumed in Kampala. In these markets, products are sold at relatively low prices compared to department stores and formal food markets, and as such, are more accessible to urban residents. Unable to deliver a constant supply, most urban farmers in Kampala channel their products through these informal markets. However, the urban food outlet faces a constant threat from the city authority. The trade ordinance 2006 ensures the eviction of informal food markets, citing a lack of hygiene in the handling, transportation and storage of food.

In addition to urban farmers, Sabiiti et al. (2014) specifies four different categories of urban agriculture practitioners in Kampala: school, health centers, prison, and police barracks. Information on the engagement of other stakeholders, particularly research institutes, and non-governmental organizations, could not be found in the literature.

Outcomes and Recommendation

Urban agriculture is practiced by 50% household in Kampala city and it is considered as a contributor to food security. Before 2005, the livestock around the city was considered a public health risk, while tall crops around cities were believed to be the reason for accidents. The city administration is gradually receiving urban farming in Kampala more positively (Sabiiti et al., 2014). The city government is gradually modifying its legal and administrative framework to make urban agriculture more viable. Urban agriculture is well recognized by government and city authority programs under the Poverty Eradication Action Plan (PEAP). The National Agriculture Advisory Services (NAADS[1]) has integrated urban agriculture into its implementation framework extending its target areas from rural to urban. Based on population density, land availability, and crop and livestock production prevalence, the KCCA rezoned the city into urban agricultural production zones, core zones, intra-urban zones, peri-urban zones. One Agriculture Advisory Service Officer in charge of the NAADS programme is assigned for Kampala city who oversees agricultural activities in the city. The city authority has leased land for the Edible Landscape Project to further support the urban agriculture in Kampala. This goal of this project is to make urban agriculture a permanent part of city planning and low-income housing design.

More recently, the National Urban Policy of 2017 proposed urban agriculture as one of the strategies for socio-economic transformation and development (Ministry of Land, Housing Urban Development, 2017). Likewise, the KCCA ongoing strategy 2020/21-24/25 has prioritized Kampala city urban agriculture as a strategy under the local economic development program. This strategy is in line with Uganda National Development Plan[2] III. The Kampala urban agriculture program is aiming to transform urban agriculture from subsistence farming to commercial agriculture [Kampala Capital City Authority (KCCA), 2020]. Kampala city has integrated urban agriculture into the city's Slum Development Plans to engage more youth in agriculture (Ruhweza, 2020).

Some recommendations include the need for city authority and central government to work together with communities and landowners to achieve planned urbanization in new sprawling areas and include community leaders at the grass root level in the planning process (Bidandi and Williams, 2020). The spontaneous and uncoordinated urban area expansion remains a challenge either due to lack of government policies, weak government regulation, weak institutions and structures, and absence of qualified urban planners. Unplanned growth of the urban boundary and lack of urbanization policy poses a challenge to Kampala city, forcing the poor to settle in marginal lands such as wetlands and low land forest around the city. Vermeiren et al. (2013) suggest that due to unplanned urbanization, the poor people will be living in steep slopes and flood-prone wetlands by 2030 or move to remote areas. Mwesigye and Barungi (2021) argue that tenure security is an essential factor for the commercialization of crops. While KCCA's ongoing strategy 2020/21-24/25 has prioritized Kampala city urban agriculture as an economic development programme, the land act has not been appropriately revised, including large-scale urban agriculture. Therefore, a balanced urban planning policy is needed in Kampala city targeting the urban poor with weak land tenure, providing a sustainable alternative for farmers who may lose land due to urban development or law enforcement (Ruhweza, 2020).

Flooding is a significant risk posing a compound threat to urban agriculture in Kampala, contributing to disease outbreaks and loss of other livelihood options. The vegetable plots near informal settlements in wetland areas are washed away by flooding. Apart from flooding, the urban farmers also listed additional climate risks such as drought, heat stress exacerbated by urban encroachment, land degradation, etc. As a result, reducing flood risk and adapting to climate change are essential goals for Kampala. Maintaining permeable surfaces through

[1]The National Agricultural Advisory Services Organization is a semi-autonomous public agency under the Ministry of Agriculture Animal Industry and Fisheries (MAAIF), responsible for public agricultural advisory/extension services.

[2]National Development Plan (NDP) is the third in a series of six NDPs that will guide the nation and deliver the aspirations of the people of Uganda, as articulated in Uganda Vision 2040. NDPIII (2020/21 – 2024/25) aims to build on the progress made, lessons learned from the planning and implementation experiences of NDPI and NDPII, and also seek to surmount some of the challenges encountered.

agriculture, wetlands, and forest remnants could help to reduce flood risk. This will help manage floods and support the urban food system (Sabiiti et al., 2014).

The informal food market contributes to affordable food for the urban poor, yet these are considered a threat by the city authority. The city authority needs to recognize the contribution of informal food markets and integrate those informal food markets into the city planning process. Likewise, informal food market actors should organize across their value chain to make their voices heard.

Case 3: The City of Cape Town, South Africa

There are three inter-related threads or narratives on challenges associated with policy and practice that emerge from the literature on urban agriculture, specific to Cape Town, when the IAD framework is applied. The first is related to the evolution of policies as the rules in use, which respond to the high levels of income inequality and food and nutritional insecurity in more than 30% of the population. Secondly, for communities that struggle with crime, domestic violence, drug abuse and high levels of unemployment, UA provides a hard to quantify sense of meaning and empowerment beyond ecological and economic benefits (Olivier and Heinecken, 2017; Kanosvamhira, 2019). The attributes of the urban farming community in Cape Town exemplify both their struggles with poverty and food insecurity, and an ability to rise above them, collectively. Thirdly, the discipline and practice of urban planning heralds a solution space that can integrate the experiences, knowledge and contributions of multiple stakeholders toward a spatial articulation of UA, within the city's landscape, and aligned with locally-driven action.

Multiple Policy Responses

In Cape Town, the policies around the thematic of UA focusses on poverty alleviation, through the food, nutrition and economic status of urban farmers. Given the high level of food insecurity and hidden hunger among the residents of informal and low-economic settlements in the city, as revealed through series of research projects aimed at understanding the nature and state of food insecurity, food security is linked at the policy level with social and economic development, and more specifically, with poverty alleviation and reduction (Battersby et al., 2011; Crush and Riley, 2018; Haysom et al., 2020).

The association of urban farming as a countermeasure against food and nutrition insecurity led to the promulgation of the Food Gardens Policy (FGP) of (2013) (Department of Social and Economic Development), in addition to the previous Urban Agriculture Policy (UAP) of 2007 (Department of Agriculture) (Kanosvamhira, 2019).

The UAP guides the allocation of inputs, resources, training and land for urban farming in the city and is aligned with the national view on urban agriculture, in that it can be crucial for poverty alleviation, by addressing food insecurity (Olivier and Heinecken, 2017). The UAP also guides activities where a group of people come together to produce food collectively, such as communities and NGOs. Soil for Life, a significant UA NGO in Cape Town has an official Memorandum of Understanding with the City of Cape Town, enabled by the UAP (Kanosvamhira, 2019). The FGP governs the establishment of sustainable food gardens to achieve food security in low-income areas. The FGP supports food gardens in Early Childhood Development Centers to provide nutritious meals (City of Cape Town, 2013). Aligned with national and provincial mandates, as well as the local government strategic priorities, the FGP envisions people to be active champions of their own development. While such arrangements extend the social capital of urban farmers by connecting them with private markets and relevant government departments (to allot land for instance), the agency of local government remains under-resourced and unrealized in such a configuration (Haysom et al., 2020). For a majority of urban farmers, UA contributes to food and income, but the scale is negligible, with famers dependent upon government support such as income grants (Paganini and Schelchen, 2018).

Secondly, farmers cite land tenure, water access, spatial fragmentation of the city (and the related problems of transport and market access), time poverty (especially among female urban farmers due to the increased share of care-giving functions they perform in families and households) and lack of self-organization into sustained formal or informal groups as critical deterrents in actualizing the economic benefits of UA (Paganini and Schelchen, 2018; Kanosvamhira, 2019). There is evidence of increased policy attention and alignment from higher levels of governance (national and provincial), domain knowledge generated through ongoing research and enquiry, and the presence of established, well-connected networks through non-state actors. However, the piecemeal solution space in the form of establishing food gardens and running time-bound projects (e.g., establishment and support of community gardens linked to early childcare centers), with limited continuity, eluded the potential of achieving a sustainable food system in the city.

Social and Personal Benefits of UA

Cape Town boasts a huge diversity among community actors in terms of struggles, cultural backgrounds, and economic status (Kanosvamhira, 2019). Collaborative work strategies sharing physical and human resources are often employed in the pursuit of community gardening, and yet there are incidents of sabotage and lack of trust, among neighbors in impoverished communities (Olivier and Heinecken, 2017). To circumvent this lack of trust, NGOs host networking events and train neighboring farmers together (Olivier and Heinecken, 2017), while also involving experienced farmers as mentors and trainers of new farmers.

The theory of social capital has been applied extensively to understand and enable the links between farmers and supporting organizations in the city, a key characteristic of the community. Three kinds of social capital, theoretically, are discussed in relation to UA in Cape Town: bonding, bridging and linking capitals (Kanosvamhira, 2019). Olivier and Heinecken (2017) note that UA strengthens household bonds, community networks and livelihood strategies among poor social groups. For example, cultivators from the same area often work together to share production costs, thus yielding collaborative livelihood strategies. Bonding capital refers to the trust and capacity for collaboration between family and friends, and acts as the first motivator but is not sufficient to keep cultivators engaged (Olivier and Heinecken, 2017). Bridging capital, which extends beyond immediate circles, to include networks between supporting organizations and cultivator groups, helps facilitate access to resources (Olivier and Heinecken, 2017). Non-state actors, such as NGOs, perform both bridging and linking functions, by connecting cultivators to markets and public institutions, that help in facilitating access to land (Kanosvamhira, 2019). Linking capital and enabling connections to markets and government are crucial for unlocking the profitability of pro-poor farming toward the long-term sustainability and scalability of UA in Cape Town.

Of the four types of farming communities (Olivier and Heinecken, 2017), the home cultivators and informal cultivator groups work through informal networks, while the institutional and community garden farmers, are able to engage with and through formal structures of the market and government departments. Through the intermediary role of NGOs, home cultivators and informal groups are able to eventually build bridging and linking capital; build trust and access resources formally. The cultivators of Cape Town have found the practice of UA to be personally empowering, uplifting and enriching, with many physical and psychological benefits being cited (Olivier and Heinecken, 2017). All elements of UA, whether formal or informal, including training of other farmers, supporting each other through difficult financial times, learning from networks beyond the immediate community, and more recently, engaging in productive activities during the pandemic, generate positive outcomes for the farmers, and contribute significantly to their sense of purpose and well-being.

Emerging Coherence Across Policy, Planning and Practice Domains

As Haysom et al. (2020) note, the majority of the South African population (63%) is living in urban areas (63%) and yet planning for food is missing from urban planning and urban governance practices. Due to the current food and nutrition policy architecture, and the emphasis on the food production for household consumption to alleviate poverty and food insecurity, not all the sustainability goals of UA are acknowledged. At the same time, locally-led efforts during the COVID-19 pandemic, in the arena of UA, show the potential for innovation and collaboration from different actors, such as NGOs, and community members (Gajjar, 2020).

The drought of 2017 has highlighted the vulnerability of UA to government-mandated water restrictions (Paganini and Schelchen, 2018), which needs to be addressed through integrated solutions, cognizant of future climate trends. In the above context, the Spatial Planning and Land Use Management Act (SPLUMA) along with planning legislation promulgated in parallel at provincial and local spheres of government since 2015, may hold the potential to address the unintended disconnect between urban planning and food system functioning (Haysom et al., 2020). Kanosvamhira (2019) also notes that sustainable monitoring and record-keeping of financial support from the provincial department is lacking; this would support greater transparency. The SPLUMA provides normative spatial development principles for collaborative decision-making across the three spheres of government. These principles include spatial justice, spatial sustainability, efficiency, spatial resilience and good administration (Haysom et al., 2020). They provide a strong basis for guiding urban governance for a sustainable food system, through for example a land-use based monitoring system.

UA in Cape Town, as with other sustainability-oriented practices, are bound to aspects of land-use and land ownership. Related to the country's apartheid past, land tenure and ownership (and housing) are highly contested, problem areas for local governments to address on their own. A *Food Sensitive Planning and Urban Design Approach* (Ilieva, 2016) posits spatial planning as the entry to address the multiple challenges faced by the various actors involved in UA; such as finance, transportation, land availability and access, spatial connectivity, and food consumption (Haysom et al., 2020). It encompasses the additional senses of time, history, human connection and meaning, often missing in policy approaches focused on agriculture as an economic sector, or urban agriculture as a means for addressing hunger and nutritional poverty. By incorporating the aspect of land availability and access to land, the foundational issue of where UA can be practiced, is brought into the space for dialogue and solution design.

Furthermore, South African cities are guided by the IUDF, 2016; which promotes the dual practice of co-operative governance (across the three spheres of government) and participatory governance (with grass-roots movements and civic groups) (Swilling et al., 2019). The "all of society approach" (IUDF, 2016) is particularly relevant for UA in Cape Town, which faces severe climate change impacts such as droughts (on a regional or national scale) and floods (on specific locations due to topographical conditions and rainfall occurrence), exacerbating the vulnerability of poor residents further.

Outcomes and Recommendations

While community and home gardens were both, at the start, supported by the UAP and the FGP, the community gardens initiative has been terminated due to lack of sustainability (Paganini and Schelchen, 2018). Home garden projects are found to support food production in low-income households (Kanosvamhira, 2019), and experienced a surge during the COVID-19 lockdown (Gajjar, 2020). These changes suggest that a closer understanding of the agency of different actors is needed to inform policies and support from state actors. Existing research through the lens of building social capital, supports the practice of UA, for personal and social well-being of impoverished households, among the vulnerable communities of Cape Town. Recent explorations into the rise of urban farming during the pandemic, indicate that there are potentials for innovation and adapting resource cycles, that support urban farmers (Gajjar, 2020).

Case-study inquiries, or funded research are considered crucial in understanding the situation across different urban farming communities in Cape Town in order to devise specific responses (Kanosvamhira, 2019). The secondary benefits and associated challenges of trust-building need greater policy attention. Thus, knowledge about the collaboration between farmers and supporting organizations will inform inclusive urban initiatives (Kanosvamhira, 2019). Further knowledge of the UA practices, and their adaptation to the constraints of the lockdown, and the opportunities yielded through them, will be important for future policy formulation and governance design.

There is a marked difference in the framing of benefits which are generated through UA, among state officials and cultivators (social and personal) (Battersby and Marshak, 2013). This difference impacts the approaches taken by state actors when engaging with UA from a policy and practice perspective, and determines the way in which community farmers engage with each other and are supported by NGOs and civil society organizations (CSOs), who serve as intermediaries across formal institutions and informal networks. Kanosvamhira (2019) also cites current agrarian approaches to food and nutrition security, that perpetuate South Africa's colonial and apartheid legacy, as well as land tenure, which poses a problem for landless urban farmers, to coalesce, relocate and be forced to rebuild social networks, when they move, as significant challenges, which prevent the potential of UA from being realized. Approaches such as food sensitive planning and urban design, enabled through the implementation of the SPLUMA for instance, could help in alleviating the challenges linked to land access, allocation, and tenure, in the context of pro-poor urban farming.

DISCUSSION

Based on the IAD framework, a set of governance factors that shape urban agriculture initiatives and their potential contribution to local adaptation have been identified for three cities in Sub-Saharan Africa; Tamale, Kampala, and Cape Town. Similar to many Sub-Saharan African countries, Ghana and Uganda have complex land tenure systems. At the city level, the implementation of land-use and spatial planning regulations, and the ability of authorities to enforce regulations, is poor. These factors have pushed UA to the margins of the law, where it is both tolerated and common. But these same factors have also created space for more powerful dynamics, including land commodification and privatization of customary land. UA is unable to compete with more profitable land uses and, consequently, farmers are relegated to occupy marginal lands for production. The establishment of farm plots in public areas, often buffer zones around water sources, such as wetlands and riverbanks, increases farmers' climate-related vulnerability, such as increased risk of flooding. Adding to this, the lack of secure land prevents farmers from investing in technology and inputs for agricultural production.

In all case studies, a lack of effective coordination among supporting actors is a fundamental barrier to the development of UA. Many challenges arose in Cape Town due to unavoidable bureaucratic regulations between the public sector and civil society. These challenges concerned farm producers' difficulties in connecting to public institutions to access services such as land for cultivation and access to markets (Olivier and Heinecken, 2017). The role of NGOs in the UA sector is found to be significant in all case studies, connecting farmers to markets and several government departments and providing training and ongoing capacity development. In the context of Tamale, Bellwood-Howard et al. (2018) recommend forming an agricultural committee of the metropolitan assembly which would host an expert group to analyze the consequences of various food system planning decisions, such as those involving agricultural land and water.

Several authors support the claim that the nature and dynamics between urban formal and informal economies, their relationship with formal governance structures, as well as the variety of planning and governance capacities shaping urban agriculture in Sub Saharan Africa need to be considered in parallel and that processes around UA development need to involve all relevant actors (Cohen and Garrett, 2010; Weldegebriel and Prowse, 2013; Eakin et al., 2014; Lemos et al., 2016; Schwan and Yu, 2018).

Healey (1997) proposed *collaborative planning* as a way in which planning institutions, processes and decisions can be reshaped to deal with a multitude of cultural and political communities. In a collaborative model of planning and policymaking, stakeholders with diverging interest can coevolve to a common understanding where they can learn from each other. Key governance stakeholders must engage in collaborative procedures to collaboratively create and implement new strategies that address a broader variety of interests and demands (Innes and Booher, 2000). This could be supported by the creation of institutions responsible for coordinating among the different sectors, e.g., ministry/departments of agriculture, water, health, land-use, poverty alleviation, (horizontal coordination) and for cutting across different levels, i.e., national, regional and local governments (vertical coordination). It is critical to take into account the various actors involved in food security governance. CSOs, for example, can contribute bottom-up knowledge to the policy-making process in order to identify food security issues and locally relevant solutions (Candel, 2014). Existing relations with community members, due to long-term association and presence, as well as proximity to (awareness of) local challenges and past experiences in addressing them, are some of the strengths that CSOs bring to the process of collaborative planning.

A learning from the cases is that *collaborative governance* is particularly relevant for UA in Sub-Saharan Africa as it shows a pathway for local governments to work alongside informal residents and workers, and women's organizations in particular, to achieve sustainable outcomes, over longer timeframes. Transdisciplinary initiatives involving researchers, farmers, government officials, the corporate sector, and others can aid in the identification of UA action-research themes relating to new technologies, techniques and approaches to address adaptation needs (Sabiiti et al., 2014).

A limitation of our methodology for exploring these case studies is its reliance on secondary sources rather than interviews with local officials and other stakeholders or other participatory methods of data collection, which would have given representation of local voices and a more updated perspective on the contemporary state of affairs in urban agriculture in the cities. However, this approach of reviewing existing literature was chosen given the exploratory context of this study. Few cities were eligible for our analysis, due to the limited and incomplete information available on the institutional characteristics shaping UA in Sub-Saharan African cities. As a consequence, the results of this study cannot be extrapolated and generalized to all Sub-Saharan African cities. It does, however, provide the framework for developing a common cross-city perspective to unpack governance factors that support or inhibit urban agriculture to achieve greater food security in urban areas.

CONCLUSION

Based on the IAD framework, a set of governance factors that shape urban agriculture initiatives and their potential contribution to local adaptation through enhanced food security, livelihood diversification and increased resilience to shocks and crises have been identified for three cities in Sub-Saharan Africa; Tamale, Kampala and Cape Town. The analysis of the case studies showed factors that compromise the ability of UA to contribute to climate change adaptation effectively. These factors often emerge from the interactions between urban development planning, land tenure systems and food security.

Our case studies emphasized the complexity of the nexus between formal and informal land systems, spatial development, and their effect on UA. In all three cities, urban agriculture is playing a significant role in food security as well as in mitigating the impact of climate change and variability. These benefits have been recognized by a wide range of stakeholders. However, due to increased pressure on land and competition between sectors, UA in these cities faces challenges to develop, maintain or even to formalize.

Our analysis points to weak implementation of land-use and land-use planning regulations and a limited ability of authorities to enforce rules in place in Tamale, Kampala, and to a lesser degree Cape Town. Weak formal land-use governance has driven UA to the legal outskirts, where its practice is both accepted and common.

A significant challenge in the establishment of UA found in all case studies is the lack of effective coordination of initiatives among supporting actors. In all case studies, NGOs play an important role in the UA sector, connecting farmers to markets and various government offices, as well as providing training and continuous capacity development.

Collaborative governance is especially important for UA in Sub-Saharan Africa because it demonstrates how local governments can cooperate with informal residents and workers, particularly women's organizations, to achieve long-term sustainability. Last, the findings of this study are not intended to be extrapolated to all cities in Sub-Saharan Africa, but they do provide a foundation for the development of a shared cross-city perspective on the governance factors that support or inhibit UA to attain higher food security in urban areas.

AUTHOR CONTRIBUTIONS

CV specifically covered the international literature review on climate risks, adaptation and links with food security, and reviewed the three cases. MV, AS, and SG wrote the three case studies drawing on existing literature on urban agriculture and food security and governance arrangements in the specific cities. MV recommended and supported the authors in applying the IAD framework to capture and communicate different aspects of the cases, also through the schematic. MV, CV, and AP reviewed and consolidated the whole manuscript. All authors contributed to the article and approved the submitted version.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2021.692167/full#supplementary-material

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Harnessing Indigenous Technologies for Sustainable Management of Land, Water, and Food Resources Amidst Climate Change

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Through advancements in technology humans have cultivated more food, used more fossil fuel reserves, polluted the environment, and caused climate change. This was not the case some few decades ago where indigenous technologies were used in exploiting natural resources. Unfortunately, the effects of climate change on the planet are no more distant reality. The melting of glaciers, rising sea levels, extreme rainfall, and prolonged drought are already being experienced. These have affected water resources, land, and food security across the world. The limits of conventional climate change adaptation and mitigation strategies call for the integration of indigenous knowledge and technologies for tackling climate change issues. This is because of the importance that indigenous knowledge and technologies have for identifying the impacts and as well providing effective adaption and mitigation strategies to climate change. Thus, this chapter explores the potential of indigenous knowledge and technologies for the sustainable management of water, land, and food security amidst climate change. The applications of indigenous technologies and knowledge such as agroforestry, the use of sacred groves to conserve water, land, and biodiversity resources, and the practising of conservation-agriculture are discussed as solutions for reducing greenhouse gas emissions, water shortages, land degradation, and pollution. However, these indigenous technologies will be less useful in today's world if not harnessed. Thus also in this chapter, the scientific know-how available to improve the effectiveness of indigenous technologies for the sustainable use of water, land, and food resources have been identified (Robotics, sensors/detectors, internet of things) and discussed.

Keywords: indigenous, climate-change, mitigation, adaptation, sustainable-agriculture

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INTRODUCTION

In this chapter, the authors explored the use of indigenous knowledge and technologies for the management of land, water, and food resources under changing weather conditions and the potentials of this knowledge/technology for climate change mitigation and adaptation. Climate change poses a major and growing threat to universal food security. The projected effects of climate change that include higher temperatures, water scarcities, land degradation, disruption of ecosystems, and the loss of biodiversity could seriously compromise agriculture's ability to feed the most vulnerable and thus impede progress towards the reduction or extermination of hunger, malnutrition, and poverty. Whilst water resources are already scarce and unsafe in some parts of the world, climate change is expected to increase the pressure on existing resources in the years to come. Climate variability and change have further exacerbated conflicts concerning access and ownership, and the use of natural resources.

Producing healthy food in a sustainable way to meet the needs of a growing world population is one of the major challenges of our time and climate change has exacerbated this. For instance by the year 2050, Sub-Saharan Africa will experience rainfall drop of about 10% and this will result in major shortages of water (Nyong, 2005) and food resources.To tackle this envisaged problem, a holistic approach to harness and diversify indigenous technologies/systems that allow for greater resilience to climate variability and change is recommended. Maintaining biodiversity for food and agriculture through the use of climate-smart-agroforestry systems is indispensable for adapting to climate change. Encouraging the conservation of genetic resources *ex situ* as well as *in situ*, especially on farms, and through conservational agriculture (climate-smart agriculture) and traditional food storage systems, are essential to build our resilience to climate change.

Also, there is a need to recognise the contribution of indigenous knowledge and practises in the maintenance of biological diversity. Integrated agricultural systems based on indigenous knowledge and traditional practises provide many examples of sustainable and adaptive systems with the potential to ensure the survival of our biota and mitigate major climatic changes. The integration of both traditional wisdom and new technologies to adapt to climate change impacts offers a path to new partnerships and innovative ways of thinking.

Climate change effects are felt significantly by rural smallholder farmers as they experience reduction in yields, crop failure, loss of assets, and livelihood opportunities (Cherotich et al., 2012). Despite such challenges, farming has continued in rural areas over the years. According to Nkomwa et al. (2014), rural smallholder farmers have been relying on their indigenous knowledge (IK) to sustain themselves and maintain their cultural identity. Indigenous knowledge systems are based on skills and practises used by local communities to predict events or situations (Jiri et al., 2015). Though indigenous knowledge offer some relief to especially short term weather variability, its usefulness is limited with regards to long term climate change effects and thus requires harnessing with modern technologies. In this regard, the usefulness of indigenous knowledge and technologies in dealing with short term weather events and how to make these technologies relevant for climate change mitigation and adaptation are discussed in this chapter.

METHODOLOGY

This chapter was written with information from available literature on indigenous knowledge, practises, and technologies and climate change. The literature search was conducted according to the procedure used by Petzold et al. (2020). The main data bases searched were Google Scholar, Web of Science and Scopus. However, some literature materials found in these data bases were under restricted-access (available at a fee). Thus to avoid information coverage limitation presented by this challenge, searches were extended to other sources including google and websites of reputable institutions and journals. The search was on all available published materials using the keywords; Indigenous, climate-change, mitigation, adaptation, sustainable-agriculture. No restriction was placed on year of publication. The search was further finetuned by the following questions.

- Which indigenous knowledge and technologies are used for weather prediction?
- Which indigenous knowledge and technology can be used for climate change mitigation?
- Which indigenous knowledge and technology can be used for climate change adaptation?
- Which indigenous conservational agriculture practises represents efficient use of land and water resources?

CLIMATE CHANGE

Climate change is the gradual change in the long-standing state of the atmosphere over several decades (Uejio et al., 2015). Globally, climate change is a concern due to its effects on sustainable development. It threatens biodiversity and ecosystems, and affects human settlements, water resources, and the frequency of extreme weather events, with substantial consequences on economic output, food production, human wellbeing, and socio-economic activities. Climate change is caused by the presence of high levels of of greenhouse gases (GHG) in the atmosphere.

Unfortunately, human activities have contributed great quantities of greenhouse gases (CO_2, N_2O, CH_4) since the industrial revolution. These GHGs act like a blanket and trap heat from the sun instead of releasing it back into space (Public Health Institute/Center for Climate Change, 2016).

Since 1990, the global GHGs emissions have increased by 1.5-fold driven by increasing fossil energy use and economic growth in developing countries. CO_2, N_2O, and CH_4 account for about 98% of the total emissions of GHGs (IEA, 2020). CO_2 has the greatest GHG effect. In 2013, 82% CO_2 GHG emissions was attributed to human activities in the United State (United States Environmental Protection Agency, 2016). Incomplete combustion of fossil fuels (coal, oil, and gas), transportation and electricity production releases the most of CO_2.

Climate change is a major challenge for agriculture (Thornton et al., 2011), water availability, food security, and rural livelihoods (Naresh et al., 2017). Also, climate change will greatly impact the quality and quantity of groundwater resources that supports 1.5–3 billion people worldwide (Kundzewicz and Doll, 2009). Its negative effects on sea levels, river flows and rainfall pattern is also anticipated (IPCC, 2008). For example in Sub-Saharan Africa, by the year 2050 rainfall might drop by 10% and this will result in major water shortages (Nyong, 2005). There are also risks of pest infestation and flooding across the world (Beddington et al., 2012).

THE USE OF INDIGENOUS TECHNOLOGIES TO PREDICT WEATHER CHANGES

Small farm holders in Africa have historically utilised several indigenous signs for weather prediction based on environmental and cultural beliefs (Ubisi et al., 2019). The most common indicators used by rural farmers are animal indicators, plant indicators, atmospheric indicators, and human ailments. These signs are used to make farm-level decisions regarding farming systems such as time of planting and the choice of crops to cultivate (Acharya, 2011; Mosime, 2018; Ubisi et al., 2019). However, the signs used can be misleading. Thus, their use especially in today's world is rather limited and require augmentation with modern technology (see Improving the Effectiveness of Indigenous Technologies Through Science section)

For instance, the appearance of a local bird known as a sparrow is an indication of rain coming in a day and the croaking of frogs indicates the highest likelihood of rain (Breuner et al., 2013; Elia et al., 2014; Ubisi et al., 2019). Though these may align with science, the scientific interpretations differ. In biology for example, the croaking of frogs is associated with mating and not rain bearing clouds though mating usually happens in the rainy season.

Many rural smallholder farmers hold the belief that excessively hot temperatures between September and December signify heavy rains (Risiro et al., 2012). With the assurance of rains from these signs, farmers choose to cultivate water-loving food crops like rice to maximise the benefits of the available water resources. These predictions also affect land management as farmers may shift their attention to wetlands leaving other areas to fallow. Livestocks may also be bred within selected areas because of the availability of fodder there and thus, control grazing is practised.

Also, indigenous farmers interpret the appearance of termites without wings together with colourful locusts as an indication of a prolonged dry spell (Chikaire et al., 2018; Ubisi et al., 2019). How this works well requires scientific investigation and results from this can be used to develop artificial intelligence biosensors/markers which provides more reliable information. This way, the indigenous knowledge is harnessed not replaced. Moreover, a hazy morning means very high temperatures should be expected during the day (Risiro et al., 2012) and a low summer rainfall indicates a warmer winter (Mapara, 2009). In preparation for the drought season, farmers may choose to use high ridges together with mulch to improve water retention in soils, planting crops (maize and sorghum) with low water requirements and agroforestry practises may also be adopted. The harvesting of rainwater for the watering of animals and crops may also be practised (Basdew et al., 2017), the shifting of planting seasons to suit the availability of rains may be the best adaptation strategy (Nkomwa et al., 2014; Soropa et al., 2015) according to water system plans (Mukhopadhyay, 2009).

Indigenous people have long known the importance of agroforestry for the management of water and land resources and for food security. The use of agroforestry by indigenous people after the prediction of an impending low rain season is because of its nutrient replenishing advantage (Rosenstock et al., 2019). The woody species within agroforestry systems (AFS) can considerably impact the water availability for agricultural crops (Rosenstock et al., 2019). This is because the roots of trees penetrate deeper into the soil than many crops and hence capable of increasing the water infiltration rate and capacity (Anderson et al., 2009). Trees and shrubs can also increase evapotranspiration by absorbing water from deeper soil layers and redistributing it towards the surface (Domec et al., 2010). This benefit crops in agroforestry systems. However, this can lead to competition, particularly in dry areas where water is a limiting factor for plant growth (Zhang et al., 2018). The wider benefit of water redistribution includes not only the upward movement of water during dry spells but also the movement and storage of excess water in the sub-surface from deeper soil layers. This makes the root system a mechanism for the balancing of soil water gradients (Burgess, 2011). Nitrogen-fixing trees and shrubs have important ecological potential in dryland forestry and are often integrated into AFS such as silvopastoral systems (Sierra et al., 2002). This contributes to sustainable agriculture by restoring and maintaining soil fertility and productivity (Bronick and Lal, 2005). The role of "fertiliser trees" and their contributions towards food production and security has been well-elaborated by Sileshi et al. (2014).

INDIGENOUS KNOWLEDGE AND TECHNOLOGIES WITH POTENTIALS FOR CLIMATE CHANGE MITIGATION

The indigenous people around the world have used several prohibitions or taboos to indirectly conserve the environment. For example, in the past, the Cherokee resisted the Tellico Dam project and also, the flooding of the Little Tennessee Valley (Whitt, 1999). Though their opposition to the project was based on the protection of their culture, it had environmental benefits such as the prevention of the release of carbon from the cutting and burning of wood, and the disturbances of stable soils. Besides the preservation of the rich biodiversity of the valley, the maintenance of carbon sinks, there is the additional benefit of the stable ecosystem (Little Tennessee Valley) holding on to its resilience against the occurrence of higher numbers of pest and diseases which are associated with climate change.

Also, the Ojibwe people (Northern America descendants) promoted the conservation of biodiversity and land by emphasising that "we take only what we need" (Chapeskie, 1999). Such believes promote the sustainable use of land, water, and food resources and prevent the excesses which lead to climate change. This also promotes the spirit of equity and togetherness and also benefits animals and plants because of the belief that nature is part of humanity and should be treated as such. With this mindset, the Ojibwe people believed that nature reciprocates what humans do to it and thus the environment is protected to prevent "curses" from nature (Climate change).

Sacred groves have also been used by some indigenous people to conserve nature and indirectly mitigate effects which could culminate into climate change. One negative effect of climate change is the loss of natural gene pools. However, mountains that are held as sacred groves/protected areas protect and hold gene pools that can be relied on when such genes are endangered outside the wild. Keeping mountains as sacred groves/protected areas enhances the development of thick forests which serve as carbon sinks and thus can mitigate the effects of climate change. Water resources within these sacred groves are also protected. The Holy Hills of south-western China are held as gardens of the gods and thus are untouched by farming and hunting (Bernbaum, 1999). The institution of such establishments can help mitigate climate change.

Moreover, sacred groves can serve as an equally effective option to modern protective measures used to protect designated areas (e.g., game reserves, forests) across the world (Bernbaum, 1999). Several forests across the developing world exist because of the reverence or sacredness given to them. In a broader sense, sacred groves serve as natural food and water buffers that can be relied on for the mitigation of the effects of climate change (e.g., water and food shortages). Sacred forests also have rich soils which when used in agroforestry systems can mitigate the problem of poor soils that are exacerbated by climate change. The establishment of sacred sites can be an effective environmental management technique for the restoration of degraded areas in the under developed world.

Indigenous people in the past have stored foodstuff and seeds in small but effective storage facilities on farms and in their homes to conserve viable seeds and for food security. These methods were devoid of today's chemical food additives. These methods could keep food and seeds between seasons and in some cases for several years. Among the most notable storage methods used included sun drying, use of salt, ash, garlic, lime powder, and dried red chilies (Prakash et al., 2016). These methods can be equally effective in mitigating the effects of climate change on humans if harnessed with modern technology. Grain detectors which work on the principles of artificial intelligence can be used to harness these indigenous practise. On the other hand, artificial intelligence programming can have algorithms which incorporates the discussed indigenous technologies as a way of making them (new technologies) acceptable to rural folks who wouldn't want to abandon their cultural practises.

INDIGENOUS KNOWLEDGE AND TECHNOLOGIES WITH POTENTIALS FOR CLIMATE CHANGE ADAPTATION

Three key highlights of indigenous knowledge and practises that are significant in native resources management include a social organisation that controls resources in the community, native methods for saving and preserving resources, and the customary norms and techniques for control, procurement, support, and transfer of natural resources (Luoga et al., 2000). Also, indigenous agroforestry hones such as the addition of leguminous trees into fallow periods between two cropping seasons (progressed fallow), or intercropping brief and long-term trees with crops (scattered intercropping), can lead to higher crop yields in numerous parts of the tropics (Hall et al., 2005).

Rural agriculturists in most of the African nations have been planting trees and when harnessed with modern tree planting technologies (DroneSeed automation tree planting) can be effective adaptation measures to climate change impact on land, water, and food resources. Agroforestry can be a level-headed land-use arrangement that explores balance/s between the raising of forests and food crops (Adesina et al., 1999). For instance, in Southern Africa, land-use conversion like the shift to game farming instead of livestock farming is encouraged (Ziervogel et al., 2008). In addition, agroforestry procedures can be used to change environmental conditions (drier conditions) through soil conditioning (organic matter content and mulch). This improve agricultural efficiency and lessens the over-exploitation of land by making possible the use of limited land space for several agricultural purposes (farming, animal rearing, aquaculture).

Accentuating on more crops that are drought resistant in drier areas may aid in minimising our susceptibility to climate change. Hence, different crops have been used by smallholder farmers as adaptation strategies to climate change in Burkina Faso, Senegal, Nigeria, and Ghana (Ngigi, 2009). Also, crop diversity may be a tall need in both flooded and non-irrigated ranges. In Darfur and Kordofan states of Western Sudan, cash crops have been replaced with food crops and crop varieties that are resilient to unfavourable climates (Akinnagbe and Irohibe, 2014). Farmers in Tanzania diversify crop types to reduce risks (Adger et al., 2003). Diversification of crops should be harnessed as a function for insurance against rainfall variability and or water scarcity. Local water-use practises (sharing water resources between man, animals, and crops) are adaptive to climate, and these should be considered whilst presenting alternatives. Soil protection strategies are progressively rehearsed in most African countries in line with adaptation to climate change.

Indigenous practises such as conservation tillage minimises the dangers from drought by minimising soil erosion, enhancing moisture retention, and minimising soil impaction. In combination, these benefits ensure resilience to climatic impacts of flood and drought. Traditional farmers have created different and privately adjusted agrarian frameworks for quite a long time, and have overseen them with native practises that were regularly successful in guaranteeing food security (Altieri, 2004). For instance, native individuals used the enormous appearance of Christmas beetles (*Anoplognathus* spp.), to predict typically or above ordinary precipitation seasons, with a chance of flooding in low-lying zones (Chanza and Mafongoya, 2018). Accepting and harnessing, native climate-smart strategies can supplement logical conventional climate services that are more reliable (Mafongoya et al., 2017).

In managing soil fertility, farmers have been using customary strategies to improve soil quality, for e.g., land fallowing (Vanlauwe et al., 2010). Also, in Lesotho, native farmers have utilised conventional cultivating systems (Machobane cultivating framework) to improve soil fertility under environmental change

(Mafongoya and Ajayi, 2017). Further, sustainability, scaling, and adoption of water-smart strategies such as harvesting of rainwater have likewise profited native knowledge systems (Reij et al., 2013). The accomplishment of such systems has been for the most part a direct result of the effectiveness of water-gathering systems with local styles, local organisations, and local social frameworks. Selection and scaling of inventive practises in natural resources management have likewise profited native information (Luoga et al., 2000).

Indigenous people have rich traditional practises and knowledge when harnessed can play an instrumental role in sustainable development and effective climate change adaptation. The practises and knowledge of the aboriginal peoples are playing significant roles in forestry and sustainable agriculture, providing ecosystem services, and protecting ecosystems for carbon storage (Oral Statement of the Special Rapporteur, 2016). This knowledge and practises of the indigenous people serve as basics for reducing emissions resulting from land degradation and deforestation. The indigenous practise of maintaining streams, rivers, dams, dugouts through taboos, and the capturing of water in drylands for livestock is now considered as adaptation strategies to combat climate change. Indigenous people also support these with hunting, gathering of wild food, and fishing (Gyampoh et al., 2019).

INDIGENOUS CONSERVATIONAL AGRICULTURE PRACTISES FOR EFFICIENT USE OF LAND AND WATER RESOURCES

Intercropping

The growing of many crop species on a land unit simultaneously using ecological concepts including competition, facilitation, and diversity is termed intercropping (Hauggaard-Nielsen et al., 2008). This practise is very productive (Hu et al., 2017). Since certain crops have varying climate adaptability, intercropping eliminates overall crop loss (Hosen et al., 2020). Singh and Singh (2017) pointed out that intercrops improve land, water, and nutrient, light, biodiversity, productivity, resiliency, and the efficient use of agro-ecosystem stability. Intercropping is a traditional agricultural practise that primarily involves intercropping legumes and crops (Daryanto et al., 2020). Hu et al. (2017) stated that wheat and maize coupled with agricultural conservational techniques decrease carbon dioxide release and upsurge crops' output. Intercropping is a cost-effective and environmentally sustainable approach for carbon sequestration while still delivering economic benefits (Wang et al., 2019). When legumes and cereals are intercropped, they enhance the easing of nutrients that are limiting (Layek et al., 2018).

Legumes have a mutually beneficial relationship with rhizobium bacteria which help fix nitrogen (Duchene et al., 2017). Applying legumes to farmlands lessens the N_2O emission of farmlands while augmenting nitrogen-holding compounds that are mineralizable in the soil (Scalise et al., 2017). N_2O is likely to increase global warming by 298-folds than CO_2, and agriculture accounts for roughly 60% of overall anthropogenic N_2O emissions (Singh and Singh, 2017). Increasing nitrogen fertilisers application alters the climate system and N cycle by emitting N_2O (De Rosa et al., 2018). Intercropping with legumes removes the application of nitrogen fertilisers and other external inputs. They increase nitrogen and phosphorus supply for crop development and nutrient quality (Latati et al., 2017). Intercropping maize with legumes lessens the leaching of nitrate and the input of inorganic fertilisers and improves soil health, crop yield, and agro-biodiversity (Reddy, 2016). Intercropping of legumes in green manure decreases soil's erodibility, thus enhancing stability in soil aggregates and encouraging N-retention in soil (De Oliveira et al., 2020).

Many reports prove that agroforestry system nutrient loss is less as compared to agriculture farming. The report by Grewal et al. (1994) shows that leucaena-napier grass had low nutrient loss than the traditional agricultural system. There was a net gain of 38 kg N, 10 kg P, and 20 kg K as compared to the net loss of 15 kg N, 2 kg P, and 14 kg K/ha in the traditional agricultural system.

In general terms, intercropping offers numerous ecosystem services including weed control, impeding disease cycles and pest outbreaks, sequestering carbon to boost soil organic matter, supporting pollinator and natural enemy populations, and helping mobilise other limiting nutrients such as phosphorus (Wick et al., 2017).

Cover Cropping

Cover cropping is a long-standing ecological technique for improving soil microbial biomass, soil health, and agro-ecosystem resources, including retention water, cycling of nutrients, carbon sequestration, weed, and pest control (Pinto et al., 2017). Cover crops are crops cultivated to shelter the ground, thus decreasing nutrient loss and soil erosion (Dabney et al., 2001). The cultivation of cover crops is between major crops to increase agricultural productivity. These are leguminous crops cultivated to cover the soil surface and aid in improving soil physical, chemical, and biological properties (Sharma et al., 2018).

Qi and Helmers (2010) observed that using cereal rye as a cover crop in a maize-soybean system improved soil water retention. Cover crops assist to minimise soil evaporation, store moisture from the irrigation and rainfall, and increase soil moisture availability to succeeding crops. Basche et al. (2016) also found that cover crops improved water retention in the soil by 10–11% and 21–22% at water potentials related to field capacity and plant accessible water, respectively. Cover crops lower the intensity of rainfall. As a result, increased water infiltration instead of drainage results and this boosts soil water storage (Sammis et al., 2012).

From 2006 to 2012, the Lithuanian Research Centre for Agriculture and Forestry ran a field study to examine the competitive ability of narrow-leafed lupine coupled with oil radish, white mustard, and white mustard combined with buckwheat cultivated as cover crops. The researchers found that white mustard cultivated alone or coupled with buckwheat was more effective for weed smothering than the narrow-leaf lupine coupled with oil radish in an organic farming system. In comparison to plots cultivated with cover crops, crops cultivated without cover crops in both low and high humus content soils had a higher quantity and biomass of weeds. The findings showed that white mustard and white mustard coupled with buckwheat were efficient in constraining volunteer plants and weed biomass in soils with low and high humus content.

The study concluded that cover crops have a ability to suppress weed development, and may be employed as a device to control weed in crops (Masilionyte et al., 2017).

Cover crops' potential to increase soil organic carbon (SOC) has been discussed in limited studies (Lal, 2004). Agricultural soils are depleted in SOC as compared to soils under natural vegetation cover. Crop cultivation leads to SOC losses of 30–40% in comparison to natural vegetation (Don et al., 2011). SOC sequestrated in conventional tillage and no-till soils can be influenced by different crop management practises due to the difference in plant carbon inputs and rate of mineralization. The SOC at 0–30 cm depth was increased to 120–130 kg Nha/year in cover crops treatment in comparison to 0 kg N/ha/year in no cover crop treatment (Sainju et al., 2006). Cover crops can decrease nutrient requirement particularly nitrogen for the subsequent crop. Nitrogen is captured by roots, and this prohibits the nitrate leaching into groundwater, and prohibit downward movement into the soil profile (Elia et al., 2014). An experiment was conducted from 1992 to 1994 in Sweden to estimate the effect of perennial ryegrass (*Lolium perenne* L.) as a cover crop sown in barley to determine nitrate leaching and availability of nitrogen to the main crop. Results showed that cover crop reduced the concentration of nitrate leaching by $<$ 5 mg/L as compared to 10–18 mg/L without cover crop (Bergstrom and Jokela, 2001). Oats (*Avena sativa* L.) and rye (*Secale cereale* L.) cover crops were evaluated with regards to reducing nitrate concentrations. Oats reduced nitrate concentration by 26% whereas rye reduced 48% nitrate concentration (Kaspar et al., 2012).

Cover crops are able to mitigate warming through greenhouse gas flux by 100–150 g CO_2 e/m^2/year which is higher as compare to mitigation through no-till. An estimation using case studies to calculate the change of surface albedo due to cover crops showed mitigation around 12–46 g CO_2 e/m^2/year over 100 years. Cover crops management help climate change mitigation through reduction of erosion from rains, retention in mineralized nitrogen due to warming, and increases soil water management options during soil saturation period or in droughts (Kaye and Quemada, 2017).

In Ghana, they are practised traditionally, and indigenous people grow pigeon pea, cowpea, mucuna, dolicos, and stylosanthes which shield the soil from erosion and weeds. Cover crops are long-term agricultural tools that recover soil–water dynamics and upsurge soil organic matter in soils (Ross, 2017). In a cropping system of maize and soybean, water content is improved in the soil (Basche et al., 2016). They improve nitrogen or recover nitrogen by fixation or mineralization, thus lessening inorganic fertilisers' input and subsequent greenhouse gases (GHGs) emissions to the agro-ecosystem (Ben-Salem et al., 2018). Cover crops that are leguminous supply nitrogen adequately to crops cultivated in rotation and decline external inputs of inorganic fertilisers (Robacer et al., 2016). Grasses and legumes are sustainable tools to support soil resources, water conservation, and nutrient cycling (Jahanzad et al., 2017). Leguminous cover crops boost soil organic matter, biodiversity, and carbon sequestration (Lal, 2011). Soil organic carbon augmentation, which involves carbon sequestration, is crucial for upsurging soil ecosystem services (Hwang et al., 2017).

Crop Rotation

Crop rotation is a historic technique used for centuries and involves farming various plants on land (Hobbs et al., 2008; Dury et al., 2012). Crop rotation is important in sustainable systems because it boosts beneficial species and interactions, breaks the cycle of pathogens, and lessens weed populations. Legumes in crop rotation provide the system with symbiotically fixed nitrogen, help in maintaining water status, and lower pathogen burden. Crop rotation has been demonstrated to have a beneficial effect on crop growth in many studies which have been attributed to changes in the bacterial community composition (Wortman et al., 2013). When compared to grains in multiple crop rotations, continuous monocropping caused changes in the soil ecosystem, increasing pathogen load and decreased the development of barley (Kennedy, 1999).

Globally, it is gaining attention to answer the upsurging agro-ecological difficulties, including decreased soil quality and climate changes due to farm methods short of rotation (Liu et al., 2016). It is a practical technique for sequestering carbon when compared to the constant farming of the same crops (Triberti et al., 2016). It potentially reduces CH_4 and other GHGs emissions in rice irrigated fields (Theisen et al., 2017). The rice cultivation in rotation with corn and sweet sorghum during the dry season, Cha-un et al. (2017) found a substantial decrease in GHGs emission by 68–78% relative to double rice cultivation. It is also a long-term method for increasing crop yields and efficient use of water while decreasing soils' erodability (Huang et al., 2003).

The rotation of crops improves soil health and the productivity of crops by changing the structure and the aggregation of soil, soil organic carbon, cycling of nutrients, and pest and disease control (Jarecki and Lal, 2003). Choosing a crop for rotation is critical, and species that improve nitrogen rises the next crop's phytomass production and increases organic matter in the soil (Singh and Singh, 2017). Increasing soil organic matter is an environmentally friendly way to boost crop productivity while maintaining the carbon cycle and improving carbon sequestration. Lehmann and Kleber (2015) found that higher amounts of organic carbon are deposited in soil than in the atmosphere and vegetation. Leguminous crops lessen the dependence on nitrogen fertilisers that releases N_2O and reducing the emission of CO_2 (Wang et al., 2019).

Additionally, such crops sequester carbon in soils (Lal, 2011). It is anticipated that the rotation of corn-soybean enhances the of crops productivity and residues relative to the monoculture of corn or soybean (Wang et al., 2019). Cowpea is a drought-tolerant indigenous crop cultivated in the semi-arid tropics of Africa, Asia, and the Americas. They are vital leguminous crops, food for both man and livestock, and efficient nitrogen fixers in sandy and nutrient-poor soils (Singh et al., 2003).

Agroforestry

Trees fix carbon during the process of photosynthesis and reserve surplus carbon as biomass (Nowak and Crane, 2002). Agroforestry is establishing trees in combination with crops and animals to economically and ecologically achieve positive interactions between different components (Nair et al., 2010). They are climate-smart practises that are generally adopted owing to their ability to improve food security, mitigate climate change, and improve crop productivity (Coulibaly et al., 2017). The agroforestry practise boosts soil organic matter, sequester carbon, retain water, farmers' income, agrobiodiversity, and agriculture productivity (Paul et al., 2017). Agroforestry systems function as atmospheric carbon sinks. When compared to agricultural plants or pasturelands, agroforestry systems trap more carbon in the atmosphere (Tomar et al., 2021). The capability of Agroforestry systems to sequester carbon is affected by various factors including age and tree species, geographical location, environmental factors, management practises, and agro-ecosystems type (Jose, 2009). Trees in croplands reduce extreme weather events, including floods, tropical storms, and hurricanes (Matocha et al., 2012) or are used as windbreaks and shelterbelts (Lasco et al., 2014).

Agroforestry practise is recognised globally as a land-use management system but common in the tropics (Pandey, 2002). It is found in Equatorial Africa, Latin America, and Southeast Asia (Szott et al., 1991). In developing countries, rural folks rely on this practise to sustain agricultural productivity and livelihoods (Meijer et al., 2015). In West and Central Africa, cocoa agroforestry is an old technique of combining forest components with crops. The multi-strata agroforestry offers agroforestry tree products, including fruits and timber (Simons and Leakey, 2004). The combination of animals into the system presents both meat and milk to the farmer, and their feces are recycled as not into manure to sequester carbon (Altieri, 1999). Agroforestry offers and not encourages several ecosystem services like improvement in soil quality, water conservation by slowing down surface runoff, reducing sediment transportation, soil biodiversity, enhances carbon sequestration, and increases various food and cover for wildlife habitat (Udawatta et al., 2017). Though these services are intertwined and difficult to quantify on their own, agroforestry potentially can promote economic, environmental, social vitality, and land sustainability (Udawatta et al., 2017). Sileshi et al. (2007) reported that when agroforestry is deliberately and appropriately planned, agroforestry practises can improve ecosystem services by modifying degraded land, climate change, and desertification while increasing the structural and functional diversity of the agricultural landscapes.

Agroforestry practises are good for drought conditions, as trees' deep roots make nutrients in the soil available for plant use (Rao et al., 2007). Agroforestry is accepted as an environmentally friendly technique for food production in the existing situation of food shortages and climate change (Mbow et al., 2014). In the drought-prone areas of the Sahel, agroforestry has grown to include the baobab (Adansonia digitata) and acacia (Acacia) trees and they are regarded as good candidate trees for agroforestry in these areas (Nyong et al., 2007).

IMPROVING THE EFFECTIVENESS OF INDIGENOUS TECHNOLOGIES THROUGH SCIENCE

The prediction of weather events and seasons with indigenous knowledge is fascinating especially when such predictions come to pass. However, there are high degrees of uncertainty associated with these predictions especially in today's world where anthropogenic activities have altered many environmental processes. The flying of sparrows today may signify a pollution event and not the ushering in of rains. Because of these changes in events, there is a need to improve our indigenous practises/technologies. However, in improving indigenous technologies care should be taken not to erase such knowledge and practices because of the need to preserve cultural heritages. Thus, new technologies incorporating the internet of things can be designed to have components of indigenous technologies in them. Smarter monitoring tools which combine the flying of sparrows and movement of locusts with changes in moisture/wind direction for weather monitoring can be produced. Such technologies will be easily accepted by indigenous people because of the inclusion of cultural beliefs and the relative ease of interpretation. These technologies can be developed based on artificial intelligence. With technologies like these in place, weather events can be better predicted and appropriate climate change mitigation and adaptation strategies readied for implementation.

Sacred groves unlike modern proctected areas gain their effectiveness from myths. Whilst science has effectively unravelled the myths behind this practise, sacred groves are still protected in many countries of the world. In some areas however people illegally exploit the resources preserved in these sacred places. To combat such illegal activities and for that matter preserve the rich land, water, and food resources in the groves, some advanced monitoring devices are required. Devices that are capable of offering aerial and terrestrial-monitoring. Monitoring in terms of trees fell, animals hunted, water pollution, and the degradation of soils. Robotics (drones) and the applications of tracer studies can present unique advantages in this direction.

Irrigation is not new to the indigenous farmer however to manage water use in this era of water scarcity, advanced technologies such as drip irrigation technology is necessary. This ensures enough water supply to crops and minimises water evaporation losses. Water abstraction from water sources can also be controlled using automated monitoring devices that ration water between several uses (watering of plants and animals). Such devices may also guide the development and maintenance of dams *vis-a-vis* the availability of lands and the priorities of beneficial communities.

The old-age farm practises of intercropping, cover cropping, crop rotation, and agroforestry can all be improved upon to make them more beneficial in the face of climate change. Effective plant-plant distances, plant water requirements, the timing of planting and harvesting can all be automated to improve yields. With modern scientific knowledge, disease-prone seeds, seedlings, and plants can easily be identified and eliminated to reduce losses. Food and seed storage methods such as sun drying can be improved upon with automated sun dryers, whiles the use of methods like the application of ash and garlic can be improved through the automated screening and selection of quality (devoid of contaminants) ash and garlic.

Information systems can also be developed to enable the sharing of information between farmers, and other land and water users. Smartphones are a practical option that can accommodate various means of communication including sign language, voice messages, graphs, videos, and alarm systems. These phones can also be designed to monitor local weather conditions and automatically trigger messages to decision-makers including farmers.

CONCLUSION

Indigenous knowledge and technologies can be useful for combating the effects of climate change on humans and other biotas. The indigenous technologies and practises that have the potential to offer some solutions to climate change problems have been identified and discussed in this chapter. After the analysis of selected indigenous knowledge and technologies, the use of changes in weather patterns, behaviour of some fauna and long standing indigenous agricultural practises were found to be useful tools and strategies for mitigating and building the resilience of communities to climate change. This knowledge and technologies are however limited in today's modern world and thus need to be harnessed using scientific knowledge and technologies (artificial intelligence, internet of things).

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.

AUTHOR CONTRIBUTIONS

All authors contributed equally to the conceptualisation, drafting, and editing of the chapter.

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REVIEW
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Aquaponics for Improved Food Security in Africa: A Review

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Increasing demand on water resources, reduced land water availability, and concerns over food security have spurred the evolution of many innovative and complex food production. An aquaponic system is a productive, innovative, and sustainable fish and vegetable production system that is revolutionizing agriculture in the face of drought, soil fertility losses, and climate change. Aquaponics, as an advanced aquaculture-agriculture system, is expected to improve food security in developing countries. However, as an emerging technology, there is very limited information on the system in Africa. Questions about the ecological and socio-economic sustainability of aquaponics are answered in this comprehensive review. This review considers aquaponics projects in Africa, categorizes the technology by evidences of their effectiveness, fish and plant yields, and juxtaposes the technology within best-use practices to make recommendations that will inform evidence-based policymaking. It also maps the present spatial adoption of the technology in sub-Saharan Africa and highlights the system's contribution to improving food security on the continent. Egypt and South Africa are countries where aquaponics is emerging and being adopted at faster rates and contributing to food security. In West Africa, significantly lower net-discounted benefit-cost ratios were realized when aquaponics systems were constructed using imported materials compared to using locally available materials. Despite aquaponics systems generally having higher start-up costs currently, its potential to be economically viable when undertaken with local materials is very high.

Keywords: agri-aquaculture, aquaculture, aquaponics, fish, plants, sustainable agriculture

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INTRODUCTION

One of the greatest challenges facing the world is how to meet the nutritional needs of a growing human population that is projected to hit 10 billion by 2050. To meet the additional food demands imposed by the nearly 30% population increase, global food production has to increase by as much as 50% (FAO, 2017). Food production will, however, be challenged by factors such as climate change, pollution and degradation of arable lands (Goddek et al., 2019a). According to the projections of Bajželj et al. (2014), despite the development of high yielding crop varieties and enhanced food production methods, current food production trends will not meet the projected global food demand by 2050. The situation will further be exacerbated by reductions in agricultural lands. Between 1970 and 2013, global agricultural lands have decreased by more than 50% (Goddek et al., 2019a). By the end of the 21st century, climate change alone is projected to account to for up to 18% of arable land losses in Africa (Zhang and Cai, 2011) which will negatively affect the continent's already dire food insecurity situation. These challenges to food production require innovation in food production systems, methods and practices, given that a billion people are already chronically malnourished (Godfray et al., 2010).

Aquaponics is a sustainable food production system that uses circular economy concepts and a biomimetic natural system to minimize input and waste. It is an industrious mechanism that incorporates impeccably with the sustainable growth of intensive agriculture (Tyson et al., 2011; Vermeulen and Kamstra, 2012; Joly et al., 2015). Aquaponics combines two primarily productive systems: recirculating aquaculture system (RAS) and hydroponic cultivation. Recirculating aquaculture involves the farming of fish and crustaceans in a tank, while hydroponic cultivation involves the cultivation of vegetables in a medium other than soil. Aquaponics emerges as a key technology with potential to transform agriculture and enhance food security in the wake of climate change, particularly in arid regions (Conijn et al., 2018).

Aquaponics in one form or another has been practiced for centuries in several countries but the technology still remains less popular compared to traditional food production methods and is largely practiced on small scales by individuals (Junge et al., 2017). The technology is, however, rapidly transforming from a largely backyard technology into industrial-scale production due to practical improvements in design and practice which have significantly increased both fish and crop output capacities and production efficiencies (Bernstein, 2011). Improvements in design and functions have transformed aquaponic systems beyond a water-reuse innovation into an efficient energy and wastewater recycling system (Goddek et al., 2019b). The technology is usually proffered as a solution for efficiently using marginal lands in urban areas for food production. Although the technology has been recommended as a means of addressing some of the food insecurity and nutrition-related challenges in Africa, its adoption across the continent is still very low. This chapter focuses on the adoption of aquaponics technology and reviews published information to highlight the potential of the technology in contributing to food security issues.

AQUAPONICS TECHNOLOGY IN AFRICA

Aquaponics systems are fairly new to countries in Africa and as expected, there are a few published information (including gray literature) on the subject obtained through online search on Google Scholar and Scopus and also by an international survey conducted in 2014 where only a single response each was received from Ghana and South Africa (Love et al., 2015). The bubble plot for the number of aquaponic publications in different African countries is shown in **Figure 1**. A total of 82 publications on aquaponics were found from 15 African

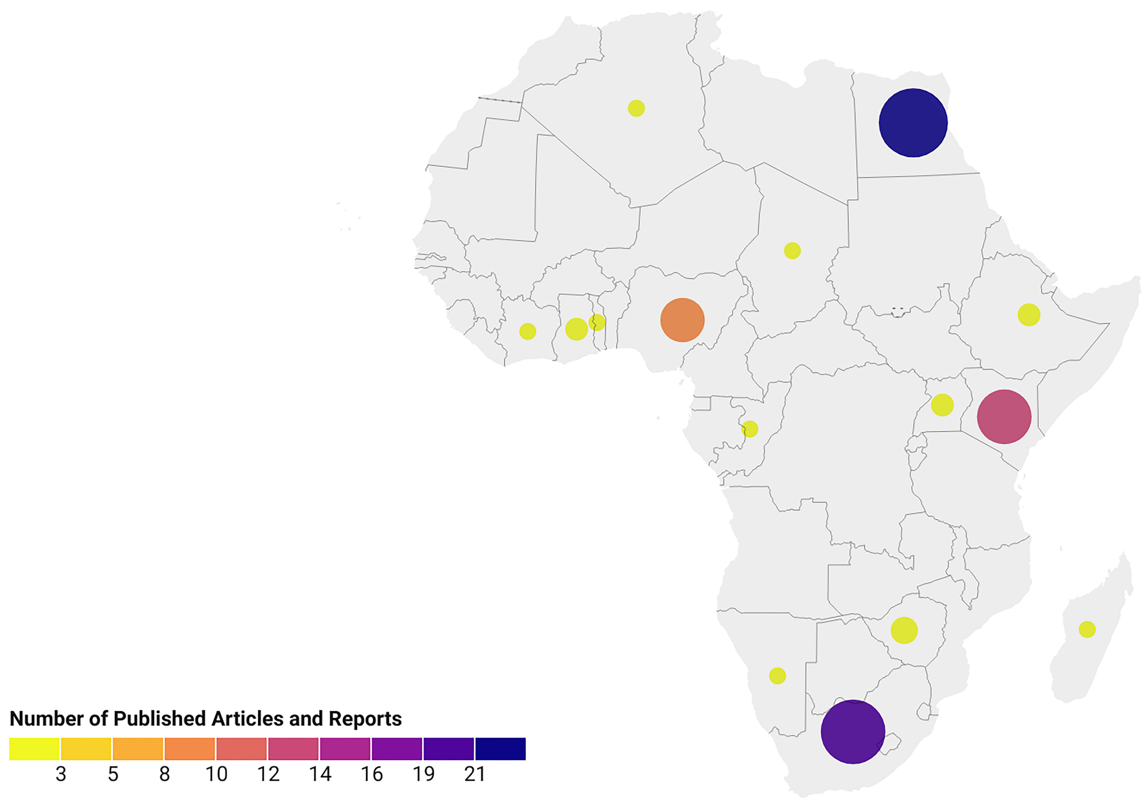

FIGURE 1 | Bubble plot showing the number of aquaponic publications in different African countries (bubble color and size indicate the number of studies in each highlighted country).

countries. Egypt, South Africa and Kenya (23, 20, and 14 publications, respectively) are the countries that appear to have widely adopted the technology in Africa. Except for Nigeria that had nine publications on aquaponics, the remaining countries had between 1 and 3 publications. The low adoption of aquaponic technology can be linked to low penetration of innovative fish production systems such as recirculating aquaculture systems that are an integral part of aquaponic systems. Adoption rates (based on the number of publications found) appear to correlate with the scale and development of aquaculture in the different countries. Egypt, Nigeria, Kenya and South Africa are major contributors to the continent's aquaculture production. Water scarcity could also be driving widespread adoption of aquaponics in an arid country like Egypt. In arid regions, circulation of water between the RAS and hydroponics units can result in a remarkable water re-use efficiency rate of 95–99% (Dalsgaard et al., 2013). The following subsections extensively review the adoption of aquaponics on a sub-regional basis across Africa. Although the review covers African sub-regions, the narrative in some instances may be skewed toward the countries that have wide-scale adoption of aquaponics.

North Africa

Water scarcity and food insecurity, combined with human population growth, pose serious challenges to North Africa's agricultural sector. Egypt's population is expected to increase from around 80 million today to around 97 million in 2025 (UN Population data), and current per capita water supply is expected to drop by 40% by 2025 (http://www.fao.org/nr/water/aquastat). According to McCarl et al. (2015), the effect of climate change on Egyptian agriculture might be very devastating. Most of the publications on aquaponics in the regions have thus touted the expansion of the technology as critical to address water scarcity issues (Essa et al., 2008; Soethoudt et al., 2016; El-Essawy et al., 2019). As opposed to traditional agriculture, aquaponics has higher economic potential and less negative effects on groundwater resources (El-Essawy et al., 2019). Commercial aquaponics units that have been coupled with greenhouses to improve crop production have been established in Egypt to grow Nile tilapia (*Oreochromis niloticus*) and olives. The feedbacks on the quality and sizes of fish produced in aquaponic units in Egypt are overwhelmingly positive and the reputation of the technology being a clean process has resulted in it rapidly gaining traction in the retail and wholesale markets (El-Essawy et al., 2019). Comparative studies on vegetable yield in the two commonly used aquaponics systems in Egypt, the deep-water culture (DWC) and sand-bed systems indicate that yields are about 30% higher in the DWC systems although this system uses lower water reuse efficiency (Salem, 2019).

While aquaponics has higher capital and operating costs than traditional agriculture in the short term, it is more profitable in the long run and saves more than 90% of the water wasted by conventional farming techniques in Dalsgaard et al., 2013 and El-Essawy et al., 2019. Profits from aquaponics systems after deducting operational expenditures are also about 30-fold higher than conventional agriculture due to the more efficient use of space and the additional income from the fish (El-Essawy et al., 2019). There is ongoing research to develop and build affordable aquaponics systems that use locally available recyclable materials to lower capital costs. Intermediate bulk containers (1,000 L capacity) are commonly used as fish culture and water treatment units in most of the aquaponics systems in Egypt as a cost-saving measure. While aquaponics has more economic and environmental benefits than drawbacks, there are technical and social limitations in addition to the high start-up investments that must be considered for it to be widely adopted in the arid regions of North Africa. According to Soethoudt et al. (2016), the development of aquaponics in Egypt is constrained by limited experience, technical expertise and scalability issues. Given the high start-up costs, it has been recommended that more research efforts should be targeted at developing units that can easily be adopted by small farms for the production of fish and crops that constitute a significant portion of local diets such as tomatoes (Soethoudt et al., 2016).

Southern Africa

The idea of aquaponics may be useful to southern African countries that have limited agricultural production resources (water and fertile croplands), high urbanization rate and exponentially increasing urban poverty (Mchunu et al., 2018). In South Africa, aquaponics has been viewed as having the potential to rehabilitate degraded coal mining sites (Botha, 2014). Another factor that has encouraged the adoption of aquaponics in South Africa is the near-collapse of freshwater pond aquaculture because outside environmental conditions do not allow cultured fish to independently establish economically viable populations (Swap et al., 2002). Water temperatures often fall below the tolerable minima required by the common aquaculture species on the continent including the Nile tilapia (Van der Waal, 2000). For year-round fish production, aquaponics installation in Southern Africa will require temperature control mechanisms or adjustments to efficiently operate. Heating costs in aquaculture generally contribute significantly to production costs.

Aquaponics is, however, an emerging but rapidly evolving practice in South Africa (Love et al., 2014, 2015; Mchunu et al., 2018). Fish stocking densities usually range from 15 to 19 kgm^{-3}, which is low and suggests small-scale or subsistence nature of most of the systems (Sace and Fitzsimmons, 2013). The wide-scale adoption of these small units is, however, very critical in addressing some of the food security issues in the country. Magazines and news articles on aquaponics in South Africa are very common and highlight the potential of the technology on hobby, small-scale and commercial levels. Commercial aquaponics in South Africa has an intensive outlook and usually adopts fish stocking densities between 60 and 200 kgm^{-3} in 5,000 m^3 tanks (FAO, 2014). The increased interest in aquaponics could also be because of the recent drought, food safety concerns, land reforms and increasing population size (Van der Waal, 2000; Faber et al., 2011; Mabhaudhi et al., 2013; Mchunu et al., 2018).

Most aquaponics operations started as aquaculture farms and then evolved to aquaponics (El-Essawy et al., 2019) and this is true for most of the South Africa establishments. Commercial aquaponics practitioners in South Africa have very good access to vegetable and fish markets (Mchunu et al., 2018). Vegetable are, however, harvested at higher frequencies of every 1–3 months compared to fish which are usually harvested at periods >6 months (Love et al., 2014, 2015). The plant component of most aquaponic system in South Africa comprise mostly salad greens, lettuce, basil, herbs, pepper, cucumber, beans and peas, tomatoes, carrots flowers and ornamental plants. While fruity vegetables have a higher economic value and return, most farmers raised leafy vegetables (salad greens, lettuce, basal, and herbs). Because of their low agronomic requirements, leafy vegetables use fewer nutrients than fruity vegetables (Rakocy et al., 2004) and grow fast when all nutrients are supplied (FAO, 2014). Moreover, leafy vegetables can be raised in higher density (up to 30 plants m^{-2}) than fruity vegetables, which usually grown at a maximum density of 8 plants m^{-2} (USAID, 2013; FAO, 2014). These plants are grown in growth medium be, nutrient film technique and deep water culture production systems. Fish sales from aquaponics are quite popular because of perceived higher product quality, growing food insecurity and dietary lifestyle changes (Faber et al., 2011; Mchunu et al., 2019). Species of tilapia and trout are the commonly raised fish in typical South African aquaponic systems (Mchunu et al., 2018). Other less popular fish include catfishes, bass, bluegill, and some ornamental species. The Nile tilapia is the most dominant species cultured in South African aquaponics (FAO, 2014; Love et al., 2014, 2015). Tilapia grows well in a recirculating tank culture with higher tolerance to fluctuating water conditions such as pH, temperature, oxygen, and dissolved solids; tilapia can tolerate a wide range of water temperatures (9–42.5°C), dissolved oxygen as low as 0.1 mgL^{-1}, and unionized ammonia concentration of 2.4 mgL^{-1} (D'Amato et al., 2007). The lower percentages for other fish species can be attributed to limiting environmental conditions in South Africa. Fish stocking densities commonly range between 15 and 19 kgm^{-3} although in some intensive systems densities can be >50 kgm^{-3} (Mchunu et al., 2018).

The nationwide survey of aquaponics users in South Africa by Mchunu et al. (2018) revealed that practitioner experiences ranged from 1 to 10 years and highlighted aquaponics as a new technology in the country. Most systems were self-constructed by the operators, sometimes with extension service assistance from the Department of Agriculture. Growth medium beds are the dominant method of crop production in South Africa (Mchunu et al., 2018) because it does not require setting up independent biofilters to remove excess nutrients from the water as the bed itself acts as a biofilter (Hu et al., 2015). Nutrient film techniques and the deep-water culture systems usually require independent biofiltration systems to facilitate nitrification, which add to the installation costs. Gravel media are the dominant method of crop production, as it is easily accessible and readily available compared to other media (Sikawa and Yakupitiyage, 2010). The flood and drain system is a cheap, simple, and easy to use method to return dissolved nutrients to the rearing tank, while giving plants enough time to take up the nutrients (FAO, 2014).

Feasibility studies have been conducted in Namibia to assess the viability of setting up aquaponics systems to enhance food security, sustainability, income generation, and as an educational resource (Rego et al., 2020). About 430,000 Namibians are reported to be food insecure as almost 70% of food is imported from South Africa (FAO, 2020). In this Namibian case, aquaponics is one of the most efficient way to combat food security (Rego et al., 2020). Aquaponic and hydroponic systems use water effectively to provide sustainable agriculture. Besides food security, aquaponics will be a sustainable agricultural system in Namibia during droughts (Rego et al., 2020). The trial runoff the prototype system indicated that tilapia and koi are the best suited fish species for aquaponics development in Namibia (Rego et al., 2020). Rego et al. (2020) found out that aquaponics would have a compound annual growth rate of 12.5% in Namibia. The study concluded that aquaponics is a lucrative agricultural system to invest in due to short- and long-term profit margins and potential local market expansions.

Facing a growing human population, inefficient traditional food production methods and unreliable rainfall, Zimbabwe is considering aquaponics as a viable means to avert famine (Marimbona and Mushiri, 2019). To offset the problem of frequent power outages and ensure continuous running of water and air pumps, a prototype aquaponics system powered by a standalone solar photovoltaic (PV) system has been tested in Zimbabwe. A 1.6 kW solar PV array produced enough output to run a combined electrical load of 293.2 W from a water pump, an aerator and electronics devices. The system used an Arduino based system to automatically monitor the temporal changes in pH, temperature and water flow velocity. The system was designed to be scalable and easy to set up in different localities.

West Africa

Literature on aquaponics in West Africa is limited compared to the Northern and Southern regions of Africa. Although internet search produces information on aquaponics from four West African countries, only a few of the publications contained enough information to be included in the review. The Sustainable Aquaponics for Nutritional and Food Security in Urban Sub-Saharan Africa (SANFU), a small-scale pilot project in Lagos, Nigeria, conducted an experiment to collect data on key variables to bring a small-scale aquaponics system to a productive and economically feasible level (Benjamin et al., 2020). This information had been up until this project been largely lacking for the sub-region. The prototype SANFU aquaponics system that was set up using relatively expensive foreign sourced components can yield about 28 kg of fish and 3 kg of vegetables per annum with a nitrogen outflow of 48.5 g. This corresponds to a rather unfavorable net discounted benefit-cost rate (DBCR) of 0.08 over a 20-year period. A similar system was setup constructed using locally sourced components had a significantly higher DBCR of 1.12. However, it is anticipated that the yield from the fish harvested can be 10 times the experimental yield if optimum real-life stocking and planting densities are considered (Benjamin et al., 2020). The SANFU study highlights the possibility of using locally available materials and increasing the chances of low-income individuals to set up small-scale aquaponic systems and contribute to food and nutrition security.

In Ghana, the implementation of aquaponic systems is slow and reports on aquaponics is very scarce. The most notable aquaponics project in Ghana was a collaborative project between a Ghanaian and Brazilian research institute, which was aimed at increasing smallholder food production through implementation of water conserving aquaponics-based food systems ensuring all-year-round food production for enhanced nutrition to the smallholder farmer (Frimpong et al., 2017). Aquaponics system may be configured to be fully recirculating or decoupled systems, and in the case of the project in Ghana, it was a decoupled system. Decoupled aquaponic are designed to culture the fish and plants as separate units whereby water is used to culture fish and the effluents supplied to the plants without circulating the water back to the fish (Karimanzira et al., 2017). In the Ghana trial, effluents from the fish production was administered to maize plots. This resulted in a maize yield of 2.3 t/ha (**Table 1**), which is higher than the maize yield range for Ghana of 1.5–1.7 t/ha (Ragasa et al., 2013). Decoupled designs allow more flexibility in customizing and optimizing the water chemistry in the effluents from the fish culture before supply to plants through supplementation of low or absent nutrients (Goddek et al., 2019b). Adding digesters to decoupled aquaponics systems can facilitate the microbial conversion of phosphorus in fish waste into orthophosphates that can be utilized by plants, with high recovery rates (Goddek et al., 2019b).

East Africa

From literature, it is apparent that aquaponics is a recent concept in East Africa. Most of the East African aquaponics trials are concentrated in Kenya. Adoption of new farming technologies that can increase climate resilience has been proposed as a way to increase food security in East Africa, particularly for subsistence farmers (Bryan et al., 2013). In Kenya, productivity of main crops such as maize is declining due to infestation of army worms, land degradation, unpredictable weather events such as prolonged dry conditions and continuous splitting of land between inheritors (Henze and Ulrichs, 2015). Food security in the 21st century requires new, innovative and sustainable food production systems that can increase crop yields using limited land and water resources with little impact on the environment and biodiversity (Pearson, 2007).

To offset the high cost of fish feed which can account for up to 70% of fish production costs (Obirikorang et al., 2020), the black soldier fly larvae (BSFL) has been experimentally included in fish feeds as substitutes for the expensive fishmeal for use in aquaponics systems in Ethiopia (Koop, 2016). Black soldier fly feeds could be suitable for use in aquaponics systems based on positive effects in optimizing fish and plant growth (Koop, 2016). van Gorcum et al. (2019) conducted an exploratory study into the demand side of the Kenyan market and consumer perceptions for aquaponically produced food products in Nairobi. Majority of the respondents in that study were willing to pay more for aquaponics products mainly because they perceived them to be fresher, healthier and free of pesticides. Based on the results of the market survey there appears to be a potential for marketing aquaponics products and the adoption of the system could represent an approach to bypass seasonal production issues due to Kenya's erratic climatic conditions. Besides market value and customer acceptance, the plants used in aquaponics are chosen based on their abilities to sufficiently recover nutrients for growth. Sweet wormwood, pigweed and pumpkin in the hydroponic component of aquaponics systems for the intensive production of Nile tilapia are able to take up nearly 74% of nitrate from the effluents from the fish production units (Gichana et al., 2018).

The challenges to establishing aquaponics projects in East Africa include lack of electricity in many rural areas, cost and access to fish feed which is the one important and most expensive inputs into the system, high set-up cost; which hinders many farmers from adopting aquaponics as most do not have access to agricultural loans. The lack of expertise and long-term planning as well as challenges related to changing customary practices undermine diffusion and adoption of new methods, tools and technologies (van Gorcum et al., 2019).

FOOD SECURITY ISSUES IN AFRICA

The United Nation's 2030 development agenda outlines 17 Sustainable Development Goals (SDGs) including SDG 2 which aims to address all forms of hunger and nutritional insecurity issues over the next decade (United Nations, 2015). Although significant progress has been made, food insecurity is still a key issue globally and over 1 billion people suffer from starvation, undernutrition and malnutrition. A disproportionate number of the people experiencing food insecurity are natives of developing countries. Whilst some African countries made significant gains in Millennium Development Goal targets such as "ending extreme poverty and hunger" and "reducing by half the proportion of people who suffer from hunger" by 2015, the large continental picture is patchy and the overall progress slow (FAO, 2015). Food insecurity reached catastrophic dimensions in some areas of Africa, particularly in the Horn of Africa and southern Madagascar (Sasson, 2012), and in some central African countries, the number of undernourished people has more than doubled since 1990 due to the synergistic effect of population growth, political instability and civil wars (FAO, 2015). West Africa has reduced the number of undernourished people by 60% since 1990 and is highlighted as one of the most successful sub-regions south of the Sahara (Hall et al., 2017). Eastern and Southern Africa also made significant progress in reducing the number of people facing food insecurity (FAO, 2015).

Food insecurity transcends insufficient food production, availability, and intake and also relates to the quality and nutritional composition of the food. Fish has often been promoted in many nutritional campaigns as a "rich food for poor people" (Beveridge et al., 2013), and plays an important role in improving Africa's food security and nutritional status. The potential of fish in improving the food security and nutritional status of rural poor, particularly of women and young children is well highlighted (Aiga et al., 2009; Longley et al., 2014; Thilsted et al., 2016; Bennett et al., 2018; Akuffo et al., 2020). Sensitization interventions tailored toward caregiver utilization of food sources like fish to improve child malnutrition has also positively affected fish consumption patterns (Bandoh et al.,

TABLE 1 | Fish and crop yields from aquaponics in Africa.

Country	Scale	Fish species	Crop grown	Fish biomass	Crop yield	References
Nigeria	Small-scale	Nile tilapia and African catfish	Spinach, eggplant and Tomatoes	27.9 kg/year	3 kg/year	Benjamin et al., 2020
Ghana	Commercial	Nile tilapia	Maize	–	2.3 t/ha	Frimpong et al., 2017
Côte d'Ivoire	Small-scale	Nile tilapia	Tomatoes	60 kg/month	81 kg/month	Gibellato et al., 2020
Egypt	Commercial		Nalta jute			El-Essawy et al., 2019
Kenya	Small-scale	Nile tilapia	Amaranthus, Cucurbita and Artemisi		1.1 kg/m^2 (Amarantus), 1.3 kg/m^2 (Cucurbita) and 1.6 kg/m^2 (Artemisi)	Gichana et al., 2018
Egypt	Commercial	Nile tilapia	Lettuce, chives, basil	5–7.5 tons/year	7.5 t/year (Lettuce), 3.2 t/year (basil), 2.6 t/year (Chives)	van der Heijden et al., 2013
Nigeria	Small-scale	Catfish	Pumpkin	160 kg/m^3	43 kg/4 months	Oladimeji et al., 2020
Egypt	Small scale	Nile tilapia	Bell and cayenne pepper, squash, cabbage, eggplant brinjal and tomatoes	35.6 kg/m^3/16 weeks	25 kg (Bell pepper), 37 kg (Cayenne pepper), 50 kg (Squash), 90 kg (Tomatoes), 180 kg (Eggplant brinjal and 180 plants (Cabbage)	Essa et al., 2008

2018). Africa's human population is the fastest growing in the world, with the population projected to reach 2.4 billion in 2050 from the present count of 1.1 billion (United Nations, 2015). This directly translates into more than half of the projected global population increase between now and 2050 being born in Africa. Africa's role in achieving SDG 2 is key to mitigating global food insecurity and several governments and sub-regional unions have made commitments to increase agricultural budgets and invest in technical solutions, high yielding crop varieties and sustainable agriculture (Sasson, 2012).

CONTRIBUTION OF AQUAPONICS TO FOOD SECURITY IN AFRICA

The current discussions on food security and sustainable food production have highlighted the "water-energy-food nexus" approach as key to analyzing and managing the interactions among global resource systems (Scott et al., 2015). The nexus approach acknowledges the interconnectedness of land, water, energy, capital and labor and their associated drivers (Joyce et al., 2019). An important element of the food security agenda in most African countries is to adopt a practice or programme that directly supports food insecure people to achieve some level of food self-sufficiency, particularly nutrition security. Mchunu et al. (2017) highlights the immense potential of aquaponics systems in ensuring food security in many areas in Africa through the provision of fish and vegetables. Fish is very important to human nutrition and health and is projected to play an essential role in the food security and nutrition discussions (Beveridge et al., 2013). The role of cultured fish in ensuring food security discussion is quite recent, and has become crucial in the face of stagnated outputs from natural waters. Even in small quantities, fish can improve the nutritional profiles of human diets by contributing essential amino acids which are often deficient in plant ingredients (FAO, 2014). The healthy macro- and micronutrient profiles of fish highlight its important role in improving malnutrition, especially among children, pregnant and lactating women (Simler et al., 2005; Béné et al., 2015). Many African nations are promoting fish culture as the answer to some of their current and future food production challenges (Robaina et al., 2019). However, the expansion of fish production through conventional earthen ponds and floating cages is constrained by several factors including limited land and water spaces, reduced water availability and concerns over environmental impact (Badiola et al., 2012). Production system diversification with particular emphasis on intensive recirculating systems including aquaponics are thus vital to the increasing fish production to meet the growing human population (Thilsted et al., 2016). Aquaponics systems have generally been projected as an innovative food system that effectively manages the food-water-energy-nexus and exceeds traditional paradigms and can resolve some of the complexities arising from sustainability and food security issues (Werner et al., 2015).

Food insecurity issues in urban areas have been projected to become worsen in Africa (König et al., 2016) leading to significant deficits in the food supply infrastructure and the creations of what has been aptly termed "food deserts" (Beaulac et al., 2009). Aquaponics implemented either as commercial enterprise or as community intervention can enhance local food production capacities (König et al., 2016). The technology is presently an emerging but rapidly growing one in Africa which is well-suited to alleviate some of the negative consequences of climate change and population growth, particularly in urban centers (Robaina et al., 2019). In the Western Cape of South Africa, aquaponics systems have been set up in urban landscapes in response to the increasing levels of food insecurity (Milliken and Stander, 2019). Poor households have been assisted to set up different scales of backyard aquaponics systems to augment food self-sufficiency and incomes. Some have in addition to growing fish and crops, added the production and sale of fingerlings and seedlings. According to Milliken and Stander (2019), increasing popularity of urban food production through aquaponics as a way to reconnect urban residents with food production improved the food self-sufficiency of these low-income communities. In space-limited urban areas, food security can be enhanced by adopting more efficient growing technologies such as vertical farming (Khandaker and Kotzen, 2018).

The drier and water-scarce regions of Africa, particularly those with limited arable lands can benefit from aquaponics given to meet food self-sufficiency while reducing environmental footprints. As part of the measures to meet the millennium development goal of eradicating extreme poverty and hunger and of ensuring environmental stability in Egypt, the country targeted aquaculture and aquaponics as viable options (United Nations, 2015). The significance of fish in Egypt's food security discussions typically correlates with increasing demands for dietary animal protein (Zwirn, 2002). Aquaponics technology has been piloted and implemented as part of the country's solution to reducing the volumes of food imports. The increased promotion of sustainable food production technologies in Egypt and other North African countries is partly as a result of the social and political unrest the region faced following periods of food insecurity and increasing food prices. To dampen the effects of fluctuating world food prices and its impacts on citizens, particularly the impacts felt by the rural poor of that country, national agencies in charge of fisheries and aquaculture have piloted small-scale aquaponics systems in rural areas and report of favorable uptake of the technology (Goada et al., 2015). There have been several private establishments in Egypt offering scalable aquaponics models aimed at improving household food self-sufficiencies. Large-scale aquaponics farms have also been established across the country, especially in the regions with pervasive water problems and limited availability of arable land. Although presently the continent-wide adoption rate of aquaponics is low, there is a high potential for increased uptake of the technology if the installation components are sourced from local materials (Benjamin et al., 2020). While most of the narrative in this section highlights the contribution of aquaponics to food security, it should be seen as a complementary technology to conventional aquaculture and agriculture since it is presently well-suited for the culture of a few fish species and has not been optimally proven to be able to support the growing of most key staple foods.

CLIMATE CHANGE, LAND AND WATER RESOURCE ISSUES

In addition to population growth, climate change is projected to significantly affect food security in Africa over the coming decades and there is robust evidence suggesting that climate change impacts will be more severe in developing countries (Tschakert, 2007). Sub-Saharan Africa is predicted to be worst affected by climate change due to the already elevated air temperatures, reliance on rain-fed agriculture and fragile local economies (Niasse et al., 2004). About 600 million people in sub-Saharan Africa will be predisposed to food insecurity and malnutrition by 2060 because 60–90 million hectares of the land is expected to experience intense drought (Sasson, 2012). Farmers have increasingly made efforts to adapt to climate change through shifting planting seasons and planting draught-resistant crop varieties but the current trends in yield improvements will not match the projected global food demand by 2050, suggesting a necessary expansion of food production areas (Bajželj et al., 2014). Expansion in agricultural land, however, appears to be impossible due to the widespread land degradation and other environmental problems. Between 1970 and 2013, the availability of agricultural land globally has decreased by more than 50% (World Bank, 2018).

Climate change is also expected to impact water availability in Sub-Saharan Africa and this will affect water-dependent livelihoods such as aquaculture. Aquaculture is the fastest growing animal sector in the world and has been identified as an important sector to successfully address the challenges to global food security arising out of the increasing human population and climate change (National Research Council of the National Academies, 2015). However, aquaculture is likely to be affected by climate change, particularly temperature increments. Unlike other farmed animals, all cultured fish species for human consumption are poikilothermic. Consequently, any increase and/or decrease of the temperature of fish habitats could have a significant influence on general metabolism and hence the rate of growth and total production.

Increased frequency and severity of droughts, floods and extreme weather events are expected to affect water availability, food security, health, infrastructure and thus overall development. Water stress leading to decreased water availability in major rivers and lakes in Asia and Africa as reported by IPCC (2007) can significantly affect both cage and pond-based aquaculture by reducing water availability and/or retention times. The predicted increases in the occurrence of extreme weather events can also lead to significant economic losses resulting from damaged fish cages and fish escapes. Due to high poverty levels, the reliance on rain or natural water bodies as water sources and the lack of access to technology and improved aquaculture practices, these impacts are likely to be severely felt in the major aquaculture regions of Africa. This coupled with conventional food production systems facing limitations for further expansion due to lack of space, reduced water availability and heightened concerns over environmental impact (Goddek et al., 2019a), has led to progressive adoption of controlled food production systems. In this context, aquaponics as a food production system that recycles nutrient and waste can address food security issues, particularly for arid regions or areas with poor agricultural soils (Goddek and Körner, 2019). As a hybrid technology, aquaponics can also mitigate some of the effects of climate change on food production.

CONCLUSION

There is no simple solution to ensuring food security, but technological innovations in food production systems can directly support food insecure people to achieve some level of food self-sufficiency, particularly nutrition security. With current food production goals no longer aimed at simply maximizing productivity but optimizing outputs across different production systems, aquaponics technology holds an immense potential in ensuring food security in many parts of Africa. Household and commercial aquaponics establishments in Egypt and South Africa have been directly linked with ensuring food security in rural and urban settings. The continent-wide adoption of aquaponics positively correlates with the level of aquaculture output. Egypt, Nigeria, Kenya and South Africa who are major contributors to the continent's aquaculture in Africa are also countries leading in adoption of aquaponics. As the continent's population continues to increase and the threats of food insecurity heightens, aquaponics represents a promising technology for producing both high-quality fish protein and vegetables in ways that utilize substantially less land, less energy and less water while also minimizing chemical and fertilizer inputs that are used in conventional food production. It is, however, imperative that more research is directed at developing low-cost aquaponics systems that can easily be adopted by low- and middle-income Africans.

AUTHOR CONTRIBUTIONS

The paper was initiated KO, BG, and WS. KO wrote the first version, provided by inputs from WS, BG, GA, and WA. All authors provided valuable inputs participated in discussions and reviewed the final draft and read and approved the final manuscript.

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Role of Climate-Smart Agriculture in Enhancing Farmers' Livelihoods and Sustainable Forest Management: A Case of Villages Around Songe-Bokwa Forest, Kilindi District, Tanzania

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Climate change and variability are happening in Tanzania, and their impacts are felt in the socioeconomic sectors, as they have resulted in the decline of agricultural productivity and increased deforestation. This study assessed the actual changes in deforestation levels and improved livelihoods caused by the adoption of climate-smart agriculture (CSA) practices. Data were collected through semi-structured household questionnaires, focus group discussions, key informants, GIS tools, and observations. Quantitative data were analyzed using Arc GIS 10.3 software, SPSS version 16.0, and Excel Spreadsheet, while qualitative data were analyzed through content analysis techniques. The findings show that farmers' livelihoods have improved and also deforestation levels decreased as a result of increased adoption of CSA during the past 30 years. Deforestation levels have been reduced from 64.6 ha per year during 1985–1995 to 11.8 ha per year during 1995–2005 and to 10.4 ha per year during 2005–2017. Further findings showed that the agricultural area had been decreased from 4,534 ha in 1995 to 4,039 ha in 2017, which is evidence that after the scale-up of CSA from the year 1992, agricultural practices were not contributing much to deforestation, while increased crop production and income were observed, which in turn supported farmers in enhancing food security, purchasing production tools, livestock, and payment for medical services, school fees, and construction of modern houses. We found that adoption of CSA systems such as agroforestry (i.e., agrisilviculture) is very crucial for improving farmer's livelihoods and reducing deforestation. Therefore, farmers need close mentoring on climate-resilient agroforestry systems, such as agrisilviculture.

Keywords: climate change, climate-smart agriculture, livelihood, forest management, Tanzania

INTRODUCTION

Climate change (CC) is currently at the forefront of debates and discourses on global environmental change (O'Neill et al., 2017). The global nature of causes and consequences of CC implies the need for international collective action for an efficient, effective, and equitable policy response (Harris, 2007). The United Nations Framework Convention on Climate Change (UNFCCC, 2008) identified two policies responsible for addressing CC, which include mitigation of CC by reducing greenhouse gases (GHGs) in the atmosphere and enhancing carbon sinks and adaptation to the impacts of CCs in the world, where climate-smart agriculture (CSA) acts as CC adaptation and mitigation intervention.

CSA refers to an approach that sustainably increases productivity, enhances resilience (adaptation), reduces GHGs (mitigation) where possible, and enhances achievement of food security and development goals (FAO, 2013). It helps people who manage agricultural systems to respond effectively to CC (Lipper et al., 2014). The CSA sustainably increases productivity and incomes without degrading forests, adapting to CC and reducing GHG emissions where possible.

Agriculture provides an important income source to the community in rural areas (Heidhues, 2001). Developing the potential to increase the productivity and incomes from smallholder crop, livestock, fish, and forest production systems will be the key to achieve global food security over the next 20 years (Sage, 2013). CC is expected to hit developing countries the hardest, and its effects include higher temperatures, changes in precipitation patterns, rising sea levels, and more frequent extreme weather events (Kifle, 2008). All of these pose risks for agriculture, forests, and food and water supplies. CSA as a resilience approach is, therefore, a predominant concern.

The CSA plays a potential role in responding to CC and variability (CCV) impacts such as withstanding prolonged and intensive dry seasons as well as in reducing pressure toward natural forests (Nyasimi et al., 2017). For example, trees in agroforestry components can increase the capacity of seasonal crops to tolerate drought and thus support farmer's food security by avoiding total crop failure in the farm (Ekpo and Asuquo, 2012). In Tanzania, CSA systems have shown good performance even in the changing climate (Pye-Smith, 2010; Charles et al., 2013; Uisso, 2015). For example, a study by Pye-Smith (2010), in the Shinyanga Region, reported restoration of the previously deforested shrubs for fodder (Ngitili) from 600 to 500,000 ha in the periods of 1980's and 1990's.

For the context of this study, agroforestry, particularly agrisilviculture, as one of CSA practices has been analyzed in the study area. This system involves the integration of trees and other large woody perennials into crops farming, with the aim of conserving trees and improving soil fertility. Various areas in Tanzania have validated the good performance and contribution of the introduced agroforestry practices (i.e., agrisilviculture) to community livelihoods and land management (e.g., Shalli, 2003; Maduka, 2007, Shilabu, 2008; Namwata et al., 2012; Ruboya, 2013), yet little has been documented and published regarding the extent of reduced deforestation due to the implemented agroforestry system in the study area. Furthermore, few studies that assessed the role of agroforestry in reducing deforestation in Tanzania mostly assumed that due to increased yield of agricultural crops and forest products on farm land, deforestation has decreased (e.g., Ramadhani et al., 2002). Ramadhani et al. (2002), also in the Tabora District, assessed the potential of rotational woodlot in improving household income and reducing deforestation and revealed that the practice supported farmers to generate additional income and had a potential to conserve 1,875 ha of forests per year. However, this has been challenged by Schroth (2004), who argued that the connections between agroforestry and use of surrounding forest areas are complicated functions, and without actually measuring deforestation rates, nothing can be really concluded about change in deforestation. However, in a study conducted in a neighboring Lushoto District, Ilomo (2014) claimed that the existing agroforestry practices were not enough for environmental conservation as whole, as majority of population still used the surrounding natural forests for their firewood needs and cleared farmland in high speed.

A study by Charles et al. (2013) in the Mwanga District assessed agroforestry as a tool in CC adaptation and revealed that the system produces a variety of products that increase farmer's resilience to climate stresses. Also, another study by Uisso (2015) assessed agroforestry as a CC adaptation option and found that agroforestry systems can help withstand the impacts of CC. The study recommended that agroforestry practices that support CC adaptation and mitigation should be given priority. The study further recommended that linking agroforestry with payment for ecosystem services schemes such as carbon credit mechanisms can enhance the adaptive capacity of agroforestry practitioners.

While these studies shed superficial light on the possible contribution of agroforestry in CC adaptation and mitigation as well as sustainable forest management (SFM), there is limited research on the role of CSA in reducing deforestation in the changing climate. Some studies like those of Ramadhani et al. (2002) and Pye-Smith (2010) assumed that due to the increased yield of crops, forest products, and adoption of agroforestry, deforestation has decreased, but the actual measured levels of reduced deforestation were not calculated in these studies. Therefore, this study sought to uncover the potential of CSA (i.e., agroforestry) in addressing deforestation problems and also enhancing crop productivity in the Kilindi District. We examined the change in deforestation levels and improved farmers' livelihoods as a result of CSA practices in the Songe-Bokwa landscape, Kilindi District. Specifically, the study (1) determined farmers' perception on CCV, (2) examined the contribution of CSA to farmers' livelihood in the changing climate, and (3) assessed the potential contribution of CSA in reducing deforestation levels.

THE CONTEXT OF AGROFORESTRY SYSTEMS AND FARMERS' LIVELIHOODS

This study is based on the conceptual framework (**Figure 1**) modified from USAID Forestry Programs (2009). The framework explains the role of land use productivity in improving livelihoods and natural resources. It further

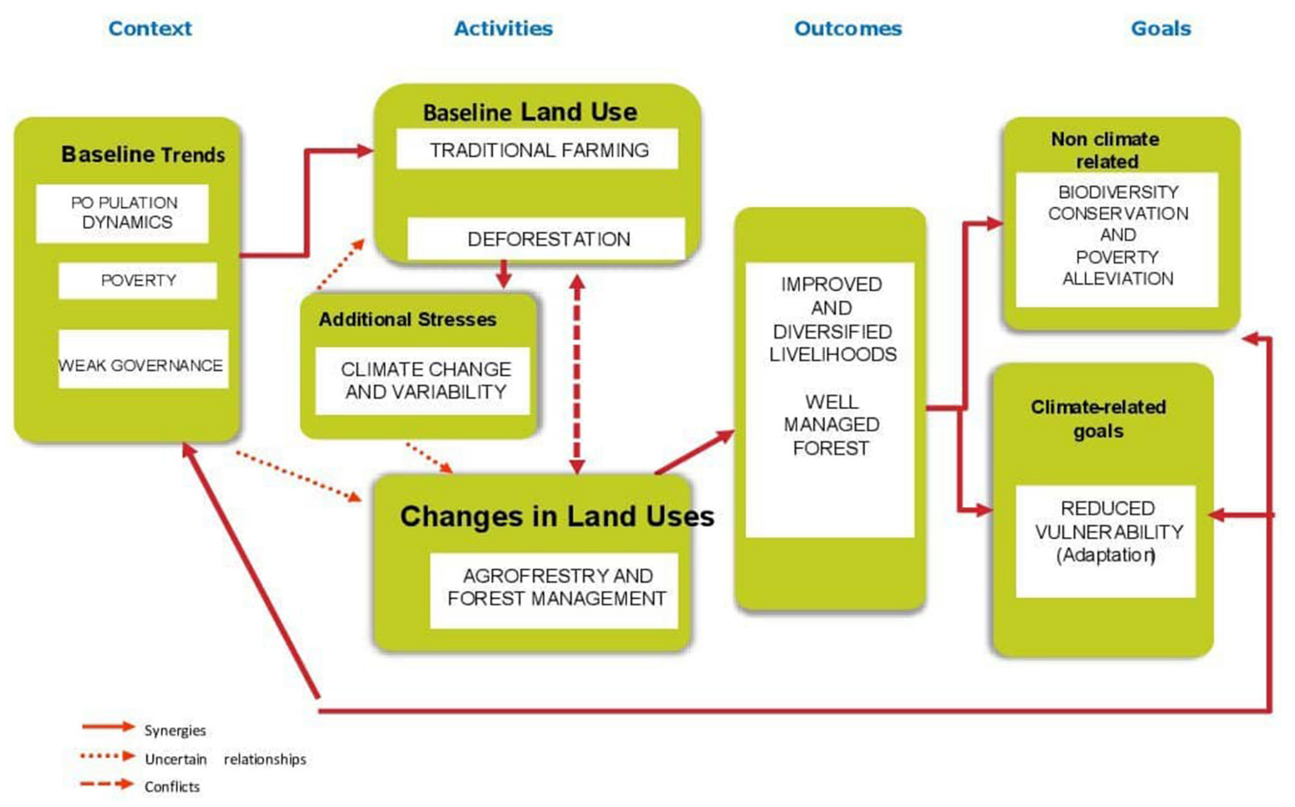

FIGURE 1 | Conceptual framework for integrating climate change in agriculture and forestry landscape.

links failure on sustainability of land use functions due to socioeconomic factors and vulnerability to climate stress, and therefore, interventions to improve land use productivity under climate stress such as agroforestry systems are assumed to enhance sustainable functioning of the landscape ecosystems.

High population growth, poverty, and limited support from the government are the main factors that drive farmers to practice unsustainable farming practices (Ndaki, 2014; Kideghesho, 2015). Farmers fail to buy agricultural inputs to maintain long-term productivity in their farm. Simultaneously, fallow periods for shifting cultivation have been reduced due to population pressure. As a result, farmers are forced to open new farms in the primary forests to maintain productivity. Moreover, CCV have been reducing crop productivity due to rapid reduction of soil nutrient and soil moisture (Pauline, 2015). This has led to crop failure, thus exacerbating the tendency of clearing of forests for fertile and moist soil as well as overharvesting of forest products to cope with food insecurity (Yanda and Mubaya, 2011; Ndaki, 2014).

To reduce food insecurity, forest degradation, and deforestation, farmers practice agroforestry as well as manage the existing natural forests. According to Ndaki (2014), farmers' willingness to implement sustainable interventions increases if they realize that their unsustainable livelihood activities will continue to affect their own livelihood. The agroforestry practices can result in better yield, as a wider variety of components are integrated as compared with monoculture farming. However, agroforestry will only have an effect on the landscape as a whole if supported by good government policy, such as land use planning and participatory forest management. The integrated and improved agriculture and forest land use will enhance better livelihoods and forest condition. Improved livelihoods and forest condition will enhance biodiversity conservation; reduce poverty and community vulnerability to climate stresses; and, thus, ensure sustainability of both agriculture and forest landscapes.

Trees integrated with crop farming provide farmers with diversity of products including crops, timber, fuelwood, building poles, fruits, fodder, and medicinal plants. These products can directly be consumed for domestic uses or used for additional income generation (Karwani et al., 2016). For example, Joseph (2015) found that in the Morogoro District, crop productivity increased after implementation of agroforestry. Likewise, Ruboya (2013) found that in the Meatu District, the agroforestry practice contributed 44 and 62% of the total household income and food produced, respectively. A study conducted in the Maswa District by Shilabu (2008) found that agroforestry is a more reliable option for sustaining food security and income than monoculture. However, due to low adoption rates of agroforestry practices in the district, the trend in increased food supply was not statistically significant. Furthermore, a study in the Gairo District by Kalineza et al. (1999) concluded that agroforestry practiced in this area was the most popular soil conservation intervention and provided multiple natural resource products to farmers.

METHODS

Descriptions of the Study Area

The study was conducted in two villages adjacent to Songe-Bokwa Forest in the Kilindi District. The forest is surrounded by four villages, namely, Bokwa, Kwamba, Vilindwa, and Songe, found in Bokwa and Kwamba wards (**Figure 2**). The district extends between latitudes 5°18′ and 5°48′ S and longitudes 35° and 37°45′ E. The district has an area of 6,443.52 km^2, and it is divided into 20 wards). The Kilindi District has a population of 236,833 people based on the last census of 2012 (United Republic of Tanzania, 2012). However, the population provided by village leaders during a household survey was 4,900 and 3,560 for Bokwa and Kwamba villages, respectively. The Kilindi District is one of the 10 districts of the Tanga Region. It is bordered by Handeni and Simanjiro Districts to the north, Mvomero and Kilosa Districts to the south, Handeni District in the eastern side, and Kiteto and Simanjiro Districts to the west.

The district is characterized by arid and semiarid climate conditions. It has two rainy seasons, the short and the long, from October to January and from March to June, respectively. The mean annual rainfall is about 750 mm, while the average temperature varies from 27 to 30°C, except for highland areas where temperatures go below 27°C. The cooler season is during June and September, while the hottest one is between December and March.

Sampling Design

The study used random and purposive sampling designs to collect both quantitative and qualitative data. The purposive sampling was used to select the two representative villages in the study area, key informants and members of focus group discussions (FGDs). Factors considered in purposive sampling included villages with the most degraded and those with healthy forests, farmers from different farming types (climate-smart and non-climate-smart practices), farming system-knowledgeable farmers, and those living in the village for at least 30 years. A simple random sampling technique was used to select households interviewed through a questionnaire. Pieces of paper with a

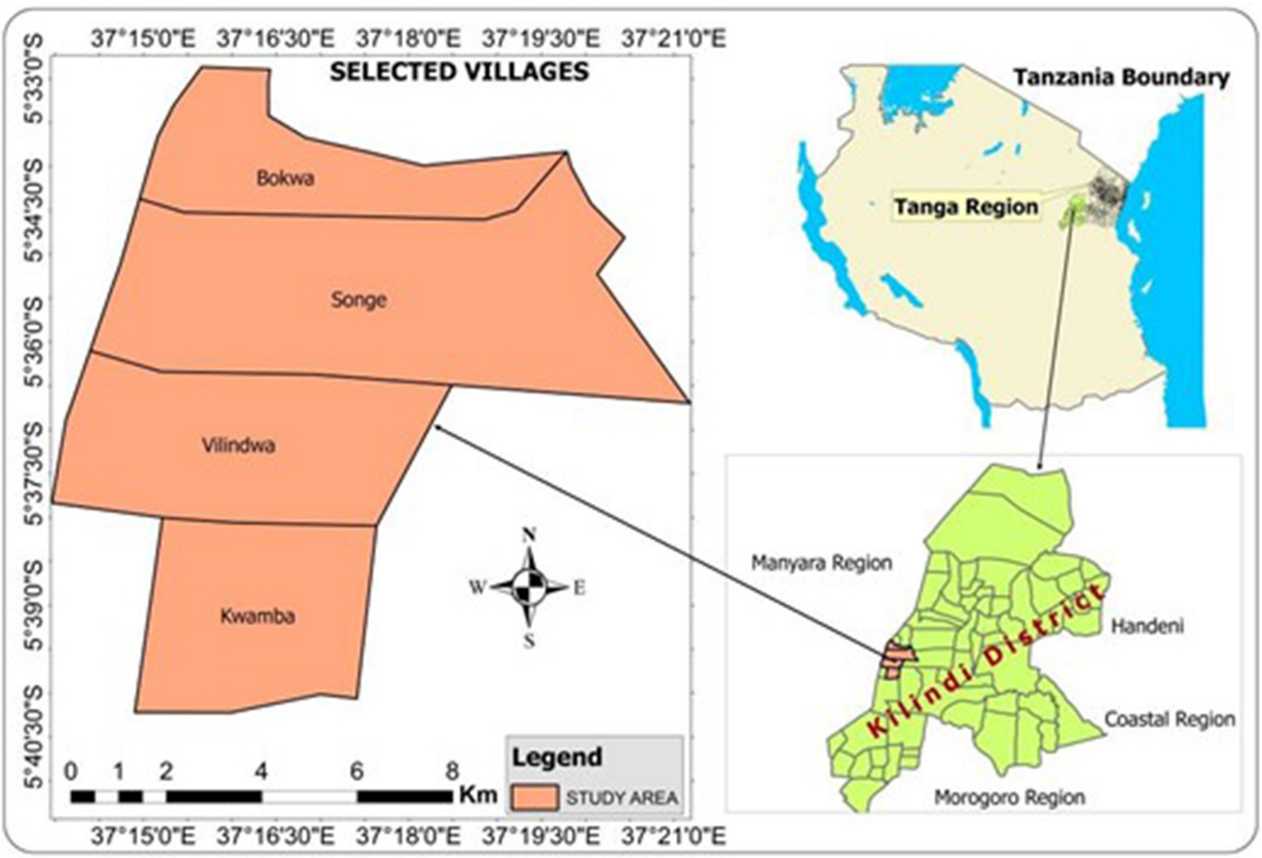

FIGURE 2 | Map of Kilindi District showing the study villages (source: IRA GIS Lab, University of Dar es Salaam, 2017).

number representing names of household heads in the village were picked randomly one by one to choose the respondents. After the papers were picked, the selected sample was assessed and confirmed to contain a reasonable representation of CSA and non-CSA farmers and a high percentage of those living in the village for at least 30 years.

The study employed a sample size of 5%. At least 30 respondents resulted from 5% of the total population in each study village. This is a valid representation according to Bailey and Mouton (1998), who recommended that for studies that use statistical data analysis, a minimum of 30 respondents is enough to represent the population.

DATA COLLECTION

Primary Data

The primary data were collected through the use of the household survey, key informant interviews, and FDGs. The tested semi-structured questionnaires were administered to household respondents. The questionnaire collected information on demographic characteristics, livelihood activities and status, agricultural productivity, forest utilization, deforestation status, the productivity of CSA practitioners, and community perceptions on CCV. Two FGDs were done in each village whereby each group comprised eight members, one group for each sex. Discussed topics include land use change, farming systems, farm productivity, forest resource availability, farmers' livelihoods for the past 30 years, and drivers for the identified changes. Similarly, necessary measures taken to improve changes in farmers' livelihoods and forest condition were also part of the discussion. Other topics discussed were the trend of CCV variables (e.g., rainfall and temperature), its impacts on farmers' livelihoods and forest conditions, and farmers' responses to impacts of CCV. Furthermore, for triangulation purposes, key informant interviews with selected village leaders and elders, ward executive officers, extension officers, ward and district agricultural officers, and forest and land officers captured detailed information on the same aspects as FGDs.

Secondary Data

Remote Sensing Data

Four Landsat Thematic Mapper (Landsat TM) images of 1985, 1995, 2005, and 2017 taken during the dry season (**Table 1**) covering Kilindi District were downloaded from United States Geological Survey (USGS) in the EarthExplorer archive. Dry-season images were preferred to facilitate differentiating the land covers easily, especially the green vegetation and water body cover (Thenya, 2001). Besides, the land use map was collected from Kilindi District Land office and saved as a reference in land use/land cover classification.

Analysis of Changes in Forest Land Use

The process involved projection of satellite images, satellite image classification, selecting training samples and signature development, supervised image classification, accuracy assessment, and change detection analysis.

- Projection of Satellite Images

The collected satellite images were pre-processed first before being analyzed; the process involved projecting them to Universal Transverse Mercator (UTM) zone 37 S, which corresponds to Tanga Region; then red, green, and blue (RGB) composite color images were created for each year. RGB was created by layer stacking, which involved Bands 2, 3, and 4 for Landsat TM 4-5 and Bands 3, 4, and 5 for Landsat 8. Each image with composite color was extracted to cover the study area by using the study area map.

- Satellite Image Classification Process

Supervised image classification was opted purposely because the whole process is controlled by the user especially on deciding the number of classes to be identified, creation of training samples, and detailed knowledge about the real study area land use and land cover distribution (Coppin and Bauer, 1996).

- Selecting Training Samples and Signature Development

The training samples representing the pixels with particular land covers were created by using polygons with the aid of GPS points, Google Earth image, and land use map of the study area. The land use classes identified were bushland, agriculture, forests, and settlements. The same training samples were stored and used to create signature file for the entire supervised image classification process.

- Supervised Image Classification

Supervised image classification was done after creation of signature file; each composite image was supplied in the so-called maximum likelihood classification algorithm as input together with the associated signature file. After the algorithm was run, the land use and land cover maps with trained classes were produced and ready for the classification accuracy assessment process. All these processes were performed on each image in ArcGIS 10.3 software.

- Accuracy Assessment

TABLE 1 | Characteristics of Landsat TM images collected.

Satellite images	Resolution	Path and rows	Season	Collection date
Landsat TM 4-5	30 × 30 m	167/064	Dry	10/7/1985
Landsat TM 4-5	30 × 30 m	167/064	Dry	2/7/2095
Landsat TM 4-5	30 × 30 m	167/064	Dry	7/7/2005
Landsat ETM 8 TIR/OLI	30 × 30 m	167/064	Dry	10/7/2017

The assessment of classification accuracy was performed on each classified map by comparing the land use classes with 25 GPS points showing the current land use (collected during ground truthing) and then creating an error matrix table; the producers, users, and overall accuracy were calculated from the table in Microsoft Excel Spreadsheet, as suggested by Coppin and Bauer (1996). Classification accuracy of min. 70% was considered acceptable. The formula used in accuracy assessment includes that of overall accuracy, user's accuracy, and producer's accuracy, whereby

Overall Accuracy = Sum of correct classified/Number of observation * 100

User's Accuracy = Total correct classified pixels in the row/Total pixels in the row * 100

Producer's Accuracy = Total correct classified pixels in the column/Total pixels in the column * 100

- Change Detection Analysis

The statistics from classified land use and land cover maps of 1985, 1995, 2005, and 2017 were used to detect the changes that occurred in a period of 32 years. Change detection involved finding the quantities of the land use/land cover changed, locations where the changes occurred, and the type of changes that occurred at a certain defined time interval (Kashaigili et al., 2006). In a post-classification process, quantitative changes were detected by comparing the successive pairs of classified maps by subtracting the quantities of the current land use class from the quantities of the past land use class; the differences obtained from each pair were converted to percentage of change by using the following formula.

Percentage on change = Area of observed change/Total area * 100

Through change detection, it is possible to deeply understand the anthropogenic interference in the land use and land cover of an area; hence, this can also help to understand the role of agroforestry in protecting natural forests.

Meteorological Data

To obtain the trend and the change of rainfall and temperature patterns in the study area from 1985 to 2017, the collection of measured monthly rainfall and temperature for the Kilindi District was necessary. These data were obtained from the Tanzania Meteorological Agency (TMA) head office in Dar es Salaam.

Data Analysis

Data in this study on the contribution of CSA to farmers' livelihoods and SFM were subjected to analysis of variance (ANOVA) using the SPSS software package (Copyright SPSS for Windows, Chicago: SPSS Inc.) to compare if there is a statistical difference in productivity between the CSA and non-CSA practitioners. Linear regression and descriptive statistics for temperature and rainfall data were run to obtain the relationship and the means, respectively, using R software. The results were presented in tables, figures, and maps. This includes data on trends of land use size, agricultural productivity, forest resource availability, impacts of CSA in livelihoods and deforestation levels, households' perceptions on CCV, and its trends for the past 32 years.

The qualitative data were analyzed using transcribing, describing, classification, and connection techniques. Transcribing involved judgments about what level of detail should be chosen from the collected information to develop specific ideas (transcripts/scripts). The transcripts were then comprehended in a form that can be easily interpreted (describing). The described data were interpreted and grouped into coherent classes (classification). Finally, connection of the data from different classes was done to get meaningful statements. Socioeconomic information helped to give details on the perceived and observed trends in climate (rainfall), agricultural productivity, agroforestry farming practices, land use changes, and their underlying drivers.

The analysis of remote sensing data utilized the supervised image classification. This involved the creation of a signature file (**Table 2**) where each composite image was supplied in the so-called maximum likelihood classification algorithm as input together with the associated signature file. After the algorithm was run, the land use and land cover maps with trained classes were produced and were ready for classification. All these processes were performed on each image in ArcGIS 10.3 software.

TABLE 2 | Description of land use/cover classification schemes.

Land use type	Attributes
Bushland	Areas with shrubs, agroforest, pasture, and thickets
Agriculture	Areas with land for crop production
Forest	Areas with natural forest
Settlements	All types of buildings

RESULTS

Main Economic Activities and Source of Income

The findings show that a relatively high percentage (60.4%) of source of household's income in the study area comes from climate-sensitive sectors (sale of agricultural crops, forest products, and livestock). The remaining 39.6% come from informal work, sale of bricks, carpentry, and formal work (**Figure 3**). This concurs with past studies showing similar findings that the majority of households source their income from climate-sensitive economic activities like crop farming (e.g., United Republic of Tanzania, 2002; Paavola, 2008; Rowhani et al., 2011).

Climate Change and Variability

Respondents perceived that CC is occurring in the study area as they witnessed repeatedly prolonged dry spells, floods, and erratic rains. The results in **Table 3** indicate that CCV had led to a decrease in crop production. **Figure 4** shows that 38.7, 18.6,

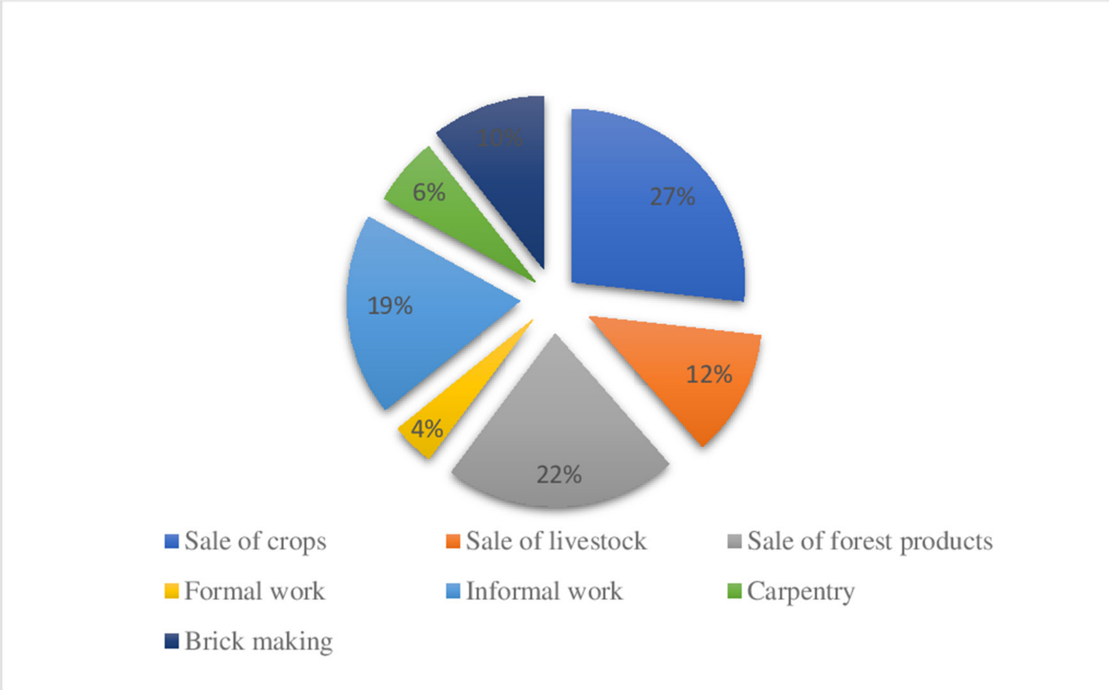

FIGURE 3 | Households' source of income based on multiple responses.

TABLE 3 | Estimate of crop harvest per acre in a bag of 90 kg during bad and good climate conditions.

Crop type	No. of responses	Bad climate condition	Good climate condition
Maize	78	4.18	11.35
Beans	78	1.95	5.54
Pigeon pea	78	1.73	3.39
Tobacco	62	12.40	17.75
Mango	67	48.34	86.73
Cassava	33	43.20	63.20

and 12.8% of households perceived that CCV resulted in food shortage, decreased income, increased disease outbreaks, youth emigration, and rise of food price.

The findings showed that 31.4% of households were still practicing non-CSA practices. About 90% of the non-CSA practices shift cultivation by clearing intact forests, thus decreasing the size of forest land. One key informant from Bokwa village stated that during critical crop failure due to climate stresses (which usually hits the majority of villagers simultaneously), the lives of most of the households depend on the forest resources. Also, as an alternative income channel during the low rainfall period, farmers cultivate tobacco in the forest where enough moisture still prevails in the soil. Unfortunately, tobacco cultivation involves clearing of forests for field and firewood used at the time of curing (drying). Also, nomadic pastoralists have been clearing forests in the area to establish a temporary settlement while looking for pasture.

The practiced CSA practices include agroforestry, conservation agriculture, integrated nutrient management, and agronomic techniques such as cover crops, improved crop varieties, drought-resistant crops, intercropping, and crop rotation.

The Rainfall and Temperature Trends

The findings demonstrated no significant variation in annual mean rainfall (mm/year) [$F_{(1,31)}$ 0.04, $p > 0.05$] between 1985 and 2017. However, the highest annual mean rainfall was recorded in 1997 (199 mm) and the lowest annual mean rainfall in 2005 (5.08 mm) (**Figure 5**).

Also, the variation of annual temperature in the study area was not significant [$F_{(1,31)}$ 0.04, $p > 0.05$]. The highest temperature was recorded in 2003, 2007, and 2009 (**Figure 6**) and the lowest in 2013 and 1989 (**Figure 7**). The lowest annual mean temperature was observed in 1985–1988, 2000–2010, and 2013–2017. The highest annual mean minimum temperature was recorded in 2003, while the lowest annual mean minimum temperature is observed in 1989. Generally, there was high variability of annual mean maximum and minimum temperature and with many recorded high temperatures from 2000 to 2010 compared with the previous years (1985–1999).

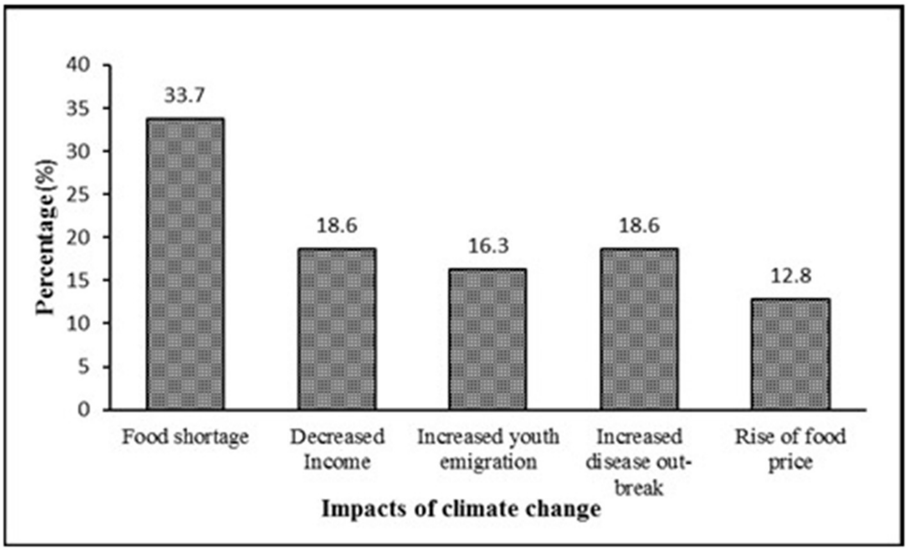

FIGURE 4 | Impacts of climate change on household livelihoods.

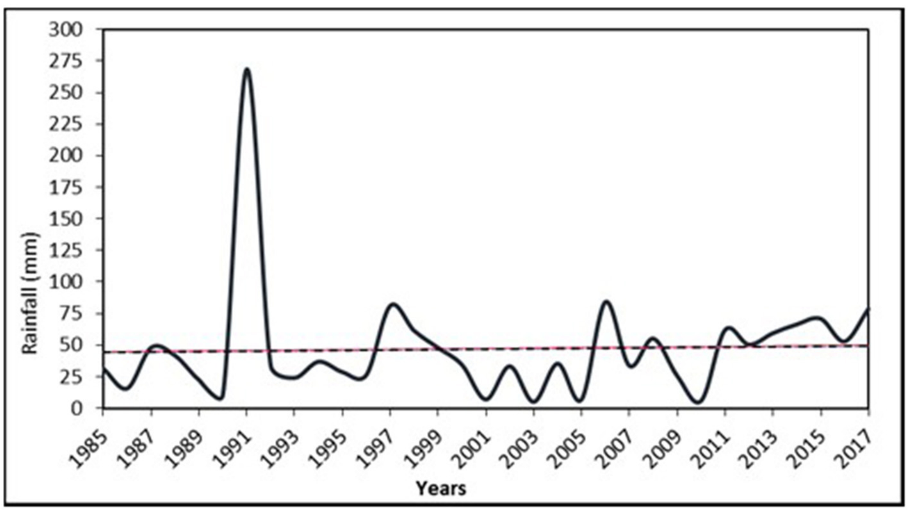

FIGURE 5 | The rainfall trend from 1985 to 2017 (presented as mean annual rainfall; source).

Contribution of Agroforestry to Farmers' Livelihoods

The productivity in farms under the practice of CSA was higher than in non-CSA farms based on *t*-test ($\alpha = 0.05$, $df = 5$, $p = 0.0431$; **Table 4**). Also, the production of crops after the introduction of CSA was higher than before the practice ($\alpha = 0.05$, $df = 5$, $p = 0.028$; **Table 5**). This trend indicated the improvement in the livelihood of agroforestry practitioners, as high crop production enhances food security, purchasing production tools, livestock, and payment for medical services, school fees, and construction of modern houses.

According to farmers, agroforestry helped them to increase crop productivity. The findings show that there is a significant increase in crop harvest after farmers engaged in agroforestry (**Table 4**). This has led to increased food security (19%), buying production tools (16%), supporting medical services (15%), improved household income (13%), purchasing livestock (13%), paying school fees (13%), and construction of modern houses (11%) (**Figure 8**). Through comparison of average crop harvest before and after agroforestry practices from the data provided by interviewed household, the study proved that there is a significant increase in crop harvest after farmers engaged in agroforestry (**Table 6**). Since crop farming is the main economic activity for 58% of households in the study area, it is logical to assume that most of the income for supporting non-food services came from selling part of the food crop.

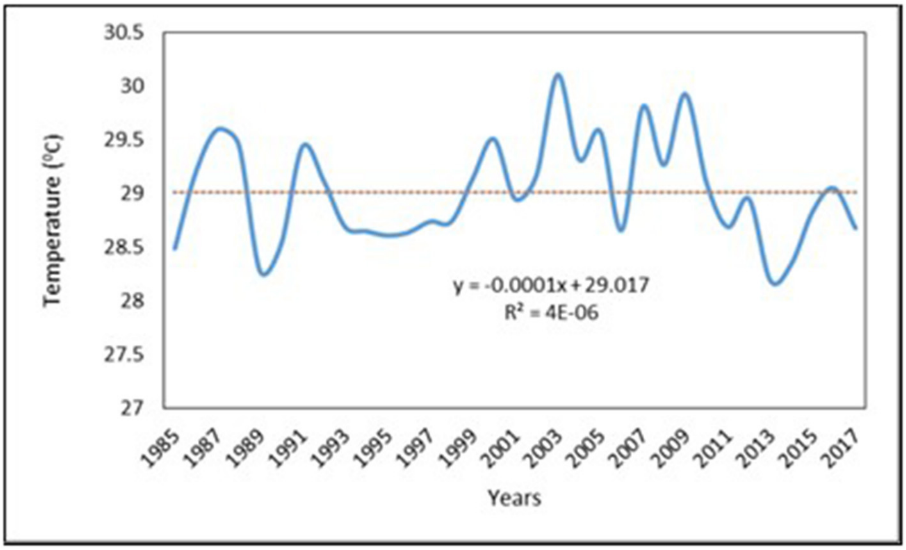

FIGURE 6 | The highest mean annual temperature recorded from 1985 to 2017.

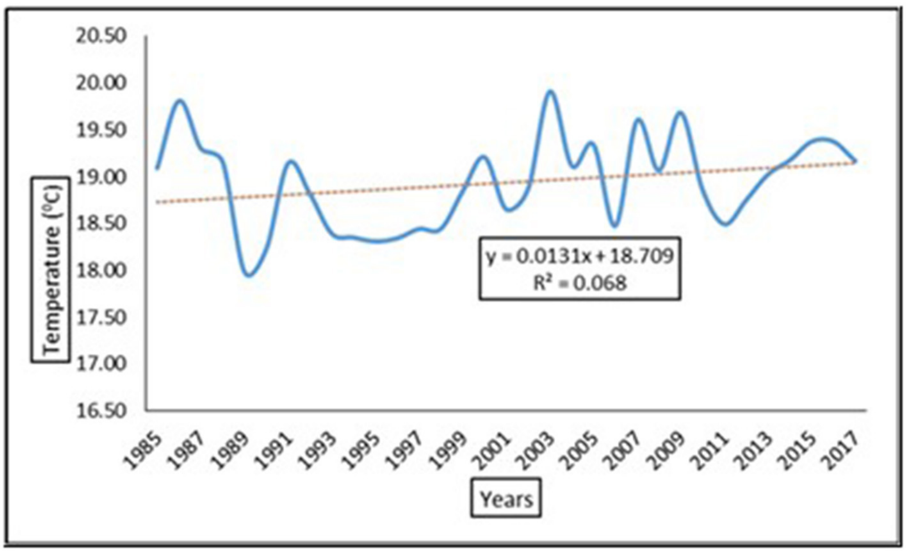

FIGURE 7 | The minimum annual temperature from 1985 to 2017.

Contribution of Climate-Smart Agriculture in Reducing Deforestation

The findings from key informants and FGDs revealed that before the intensification of CSA practices in the 1990's, there was a high rate of deforestation. It further affirmed that from the 2000's onwards, the rate of clearing forests for opening new farms has been decreasing due to the adoption and practice of CSA. Key informants also elaborated that the establishment of the Kilindi District resulted in high demand for land for settlements. Settlements occupied much of the agricultural area and forced some farmers to open new farms in the forests to compensate for the lost farming areas. Maps from satellite images also show that deforestation levels during the period of 1985 to 2017 have decreased (**Figures 9A–D**). In the period from 1985 (**Figure 9A**) to 1995 (**Figure 9B**), 646 ha of forest disappeared; from 1995 to 2005 (**Figure 9C**), only 118 ha disappeared; and from 2005 to 2017 (**Figure 9D**), deforestation went down to 104 ha. Further findings showed that the agricultural area had been decreased from 4,534 ha in 1995 to 4,039 ha in 2017, which is evidence that after the scale-up of CSA from the year 1992, agricultural practices were not contributing much to deforestation (**Table 6**). Other factors that might have contributed to a decrease in

TABLE 4 | Comparison of crop production between CSA and other farming practices.

Crop	Harvest in non-CSA			Harvests in CSA		
	Min	Max	Mean	Min	Max	Mean
Maize	3.0	15.0	8.678	5.0	20.0	13.220
Beans	1.0	8.0	3.580	2.0	15.0	8.356
Pigeon pea	1.0	8.0	3.085	2.0	14.0	6.220
Tobacco	7.0	20.0	12.651	1.0	20.0	16.766
Mangoes	10.0	95.0	53.315	10.0	110.0	60.315
Cassava	2.0	15.0	38.103	4.0	30.0	61.621

CSA, climate-smart agriculture.

deforestation include the level of community awareness on SFM, law enforcement, and limited suitable forest landscape for opening farms. Also, findings indicate that during 1985–1995, the size of the agricultural area had increased by 3,721 ha; during 1995–2005, it increased by only 11 ha; and thereafter, the size of agricultural land decreased by 506 ha during 2005–2017. This is an indication that from 1995 to 2005, agricultural activities contributed very little to deforestation, while during 2005 to 2017, agriculture did not have any direct contribution to deforestation. However, key informants reported that during 2005 and 2017, some forests converted into new farms as part of agricultural land were converted to settlements. Also, it had been noted that during 2005–2017, the size of bushland, forest, and agricultural land were decreasing, while the area for settlements increased.

TABLE 5 | Comparison of crop harvest per acre in a bag of 90 kg for climate-smart farmers before and after engaging in CSA interventions.

Crop type	No. of responses	Before CSA practice	After CSA practice
Maize	56	5.21	11.02
Beans	56	2.86	6.41
Pigeon pea	47	2.52	4.43
Tobacco	36	12.34	17.05
Mango	53	57.23	74.15
Cassava	42	41.22	64.82

CSA, climate-smart agriculture.

DISCUSSION

Repeatedly prolonged dry spells, floods, and erratic rains confirmed respondents' perception that CC is happening in the study area. This perception was congruent with observed rainfall records from the Kilindi District as reported by Mjata (2015). The study revealed that there was rainfall variability, a shift in rainfall patterns, and an increase in temperature since the 1980's. Also, the study of Magreth and Bushesha (2017) on the potential of forest resources on adaptation to CCV in the Kilindi District revealed that farmers perceived that CC has prolonged droughts and shifts in rainfall patterns. Similar perceptions have been given by farmers in the Great Ruaha sub-basin: rainfall pattern is fluctuating and temperature increases (Pauline et al., 2017, Pauline and Grab, 2018). Likewise, farmers perceived that CC affects agriculture, forestry components, other environment components, and household livelihoods. The findings show that CCV led to a decrease in crop productivity. The study by Yanda et al. (2005) observed a similar trend that in Tanzania, CCV has caused a general decline in crop productivity.

The climatic conditions leading to a decrease in crop harvesting includes decreased rainy days, prolonged dry spell, floods, and unpredictable (early and late) rainfall onset. The findings from key informants and FGDs revealed that low rainfall triggers pest and disease outbreaks. During field observations, it was confirmed that crops had been attacked by pests and affected by floods. It was also highlighted that despite CCV, loss in soil fertility and moisture in the farms was attributed to low knowledge and limited capital for practicing sustainable farming methods. The perceived CCV increased the rate of soil moisture and nutrients loss and thus exacerbated the decrease in crop productivity. Other studies including Yanda and Mubaya (2011) and Ndaki (2014) also concluded that climatic stress intensifies the loss in soil moisture and nutrients leading to food insecurity and degradation of the natural resources. One key informant from Kwamba village stated that "we used to abandon a piece of land for about 8 years to restore its fertility, but presently we can only leave it on fallow for not more than 4 years." This agrees with the findings of Kilawe (2016) that in Kilosa traditional shifting cultivation in Tanzania is mainly transformed into short fallow and permanent monoculture.

Furthermore, findings show that CCV affect some agricultural components. The annual crops and livestock are major victims than the trees. In one of the farms in Bokwa village, it was observed that sugarcane had been eroded by floods while the trees in the same field withstand the impacts. This finding is supported by Thorlakson and Neufeldt (2012), who also found that trees had been more resilient to extreme weather events such as floods and drought and thus helps to reduce the risk of crop losses.

Farmers perceived that CC resulted in increased pest outbreaks, a rise in temperature, deforestation, decreased water table, and a decline in rainfall. The findings from FGDs affirmed that during critical crop failure, some farmers have been relying on charcoal making, which involved clearing the forests, and most of the water wells around the cleared forests dried. Similarly, Ndaki (2014) reported the same incidence that during the periods of crop failure, the rate of cutting of trees for charcoal making increased to provide an alternative source of income.

Also, households perceived that CC affects household livelihoods. According to them, it resulted in a shortage of food, a decrease in income, youth emigration, increased disease outbreaks, and increased cost of food. A similar situation was also noted in the Great Ruaha River sub-basin that the shift in rainfall onset affected the normal growth of crops leading to reduced crop yield to the extent that farmers faced food insecurity (Pauline et al., 2017; Pauline and Grab, 2018). Likewise, Ndaki (2014) in his study of CC adaptation strategies at Mkomazi sub-catchment found similar results regarding out-migration. An increased number of men temporarily moved to the nearby towns in search of casual work to sustain their households during prolonged dry seasons. Liwenga (2003) in a study on rainfall-induced crop failure, food insecurity, and out-migration in Same-Kilimanjaro found that when farmers faced food insecurity, they migrated outside the village to find alternative livelihoods.

In response to the decline in crop productivity and deforestation, farmers practiced CSA practices such as agroforestry (i.e., agrisilviculture), conservation agriculture, integrated nutrient management, and agronomic techniques such as cover crops, improved crop varieties, drought-resistant crops, intercropping, and crop rotation. The findings from household interviews showed that farmers engaged in CSA to solve the problem of food insecurity, reduce dependency on forest resources, and increase household income. Farmers in both Bokwa and Kwamba villages commented that CSA was

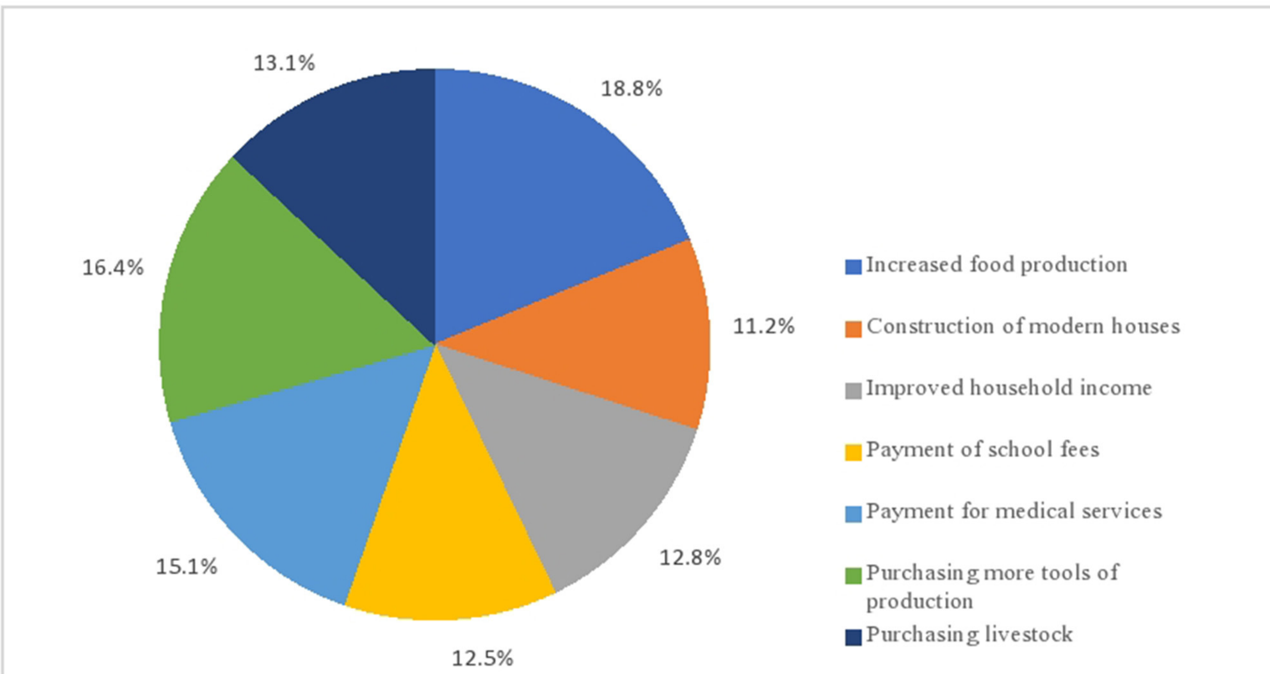

FIGURE 8 | Improved livelihoods due to agroforestry.

TABLE 6 | Land use/cover area distribution in Kilindi District between 1985 and 2017.

Years	1985		1995		2005		2017	
Land cover class/area	Ha	(%)	Ha	(%)	Ha	(%)	Ha	(%)
Bushland	6,276	67.01	2,690	28.72	2,716	29.00	2,484	26.52
Agriculture	813	8.68	4,534	48.41	4,545	48.53	4,039	43.12
Forest	1,471	15.71	825	8.81	707	7.55	603	6.44
Settlements	806	8.61	1,317	14.06	1,398	14.93	2,240	23.92
Total	9,366	100	9,366	100	9,366	100	9,366	100

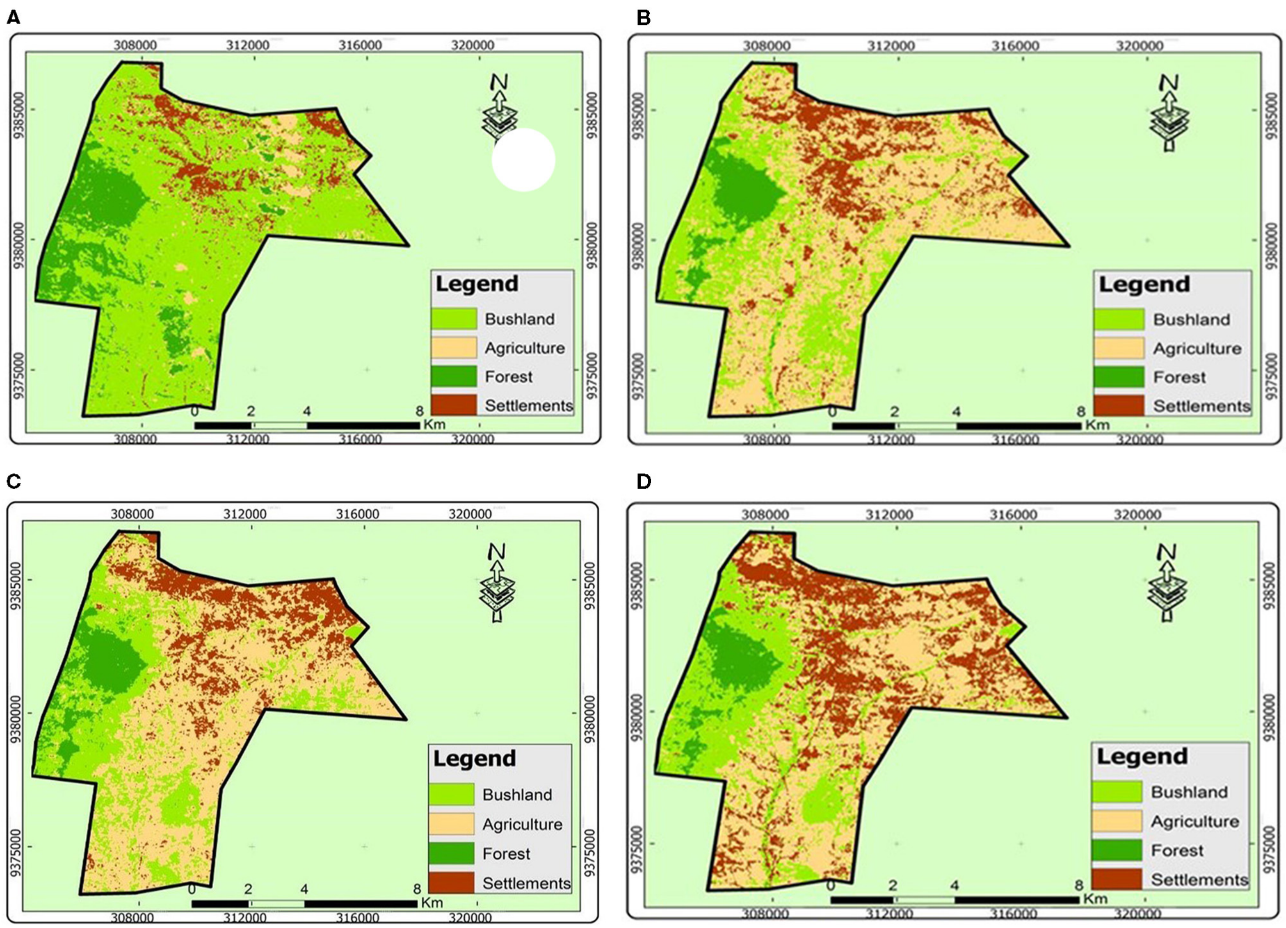

FIGURE 9 | Land use/land cover for the study area: **(A)** 1985, **(B)** 1995, **(C)** 2005, and **(D)** 2017.

beneficial, as it withstands the negative impacts brought by CCV. One non-climate-smart farmer witnessed that during prolonged dry spells, most of those who were not practicing CSA have faced total crop failures, while those practicing agrisilviculture harvested at least limited crops and fruit from their trees. During field visits, it was observed that trees were less affected by climatic stress than were other crops. These findings were also affirmed by Charles et al. (2013) and Mngumi (2016) that practicing monoculture is seen as a risk in bad climatic conditions, which results in crop failure or damage.

A notable increase in crop harvest after farmers engaged in CSA was recorded in the study area. Farmers were food secured and gained more income through sales of their crops. They used part of their income for paying school fees, buying production tools, supporting medical services, purchasing livestock, and paying house construction. This made CSA farmers more resilient to negative climatic effects. The results are similar to findings from other studies (Shalli, 2003; Maduka, 2007; Shilabu, 2008; Namwata et al., 2012, Ruboya, 2013) that found that CSA practices contributed additional household food and income to normal agricultural practices. Mahenge (2014) compared the productivity of conservation agriculture and conventional farming in Southern Uluguru mountains and found that the marginal productivity of land for conservation agriculture farmers was 366 kg/ha while that of conventional agriculture farmers was 248 kg/ha. Maize species resistant or tolerant to maize streak virus in Central Tanzania proved to have yielded potential ranging from 2.5 (Kito) to 6.25 t/ha, while the local breed is almost yielding nothing when attacked by maize streak virus (Kaliba et al., 1998). Another study by Ilomo (2014) in the Lushoto District revealed that 17.7% of the respondents' annual income has increased since they started CSA. The result lines with that of Charles et al. (2013) who revealed that CSA practices in the Mwanga District gave farmers benefits such as food, fodder, and additional income from sales of livestock, fruits, and timber. Likewise, Joseph (2015), in a study on the effectiveness of CC mitigation interventions in Morogoro District, revealed that the average crop production per acre has increased after farmers started practicing CSA. A related study by Ekboir et al. (2002) in Ghana found that no-tillage farming (conservation agriculture) supported 62% of farmers to increase crop yield in maize, cassava, rice, sorghum, and related crops. Intercropping and crop rotation in Kenya resulted in a 71% maize yield increase. Verchot et al. (2007) reported that in Malawi, agroforestry intervention resulted to increase in maize yield from 0.7 to 1.5 t/ha. Another related study by Nguyen et al. (2013) in Vietnam found that while rice and other rain-fed crops suffered over 40% yield losses in years of extreme drought or flood, tree-based systems and cattle were less affected. The trees provided income, food, feed, and other environmental benefits; thus, agroforestry systems, with high resilience and multiple benefits, made farmers food secure during extreme climatic conditions. Moreover, Lasco et al. (2014) studied the role of trees and agroforestry in reducing smallholder farmer's exposure to climatic risks in Philippines and found that agroforestry resulted in improved crop productivity, diversification of food sources, and increase in income. Also, Rahman (2017) studied the impacts of incorporating trees in smallholder farms in Bangladesh and Indonesia and found that 73% of the 176 tons of fuelwood used annually were sourced from agroforestry tree components established through short rotation coppice technology.

The change in forest size observed in the study area was linked to the settlement expansion, farms, and charcoal making. Opening farms in the intact forests was partly preferred as an adaptation strategy to the loss in soil moisture and nutrients due to extreme temperature. To reduce the rate of deforestation caused by the opening of new farms, farmers engaged in CSA practices. The findings from key informants and FGDs revealed that before the scale-up of CSA practices from the 1990's, there was a high rate of deforestation due to regular expansion of the farming areas. But from the 2000's onwards, the rate of opening new farms by cutting forest has been decreasing, as a high percentage of the farmers are no longer practicing shifting cultivation. This is because CSA components retain soil moisture and nutrients that help in the growth of the annual crops.

The findings show that forest size has not stopped decreasing, but deforestation levels have decreased. Land use/cover maps for 1985, 1995, 2005, and 2017 for the study area show significant changes in forest size. The findings indicate that the deforestation levels from 1985 to 1995, 1995 to 2005, and 2005 to 2017 were 646, 118, and 104 ha, respectively. Information from key informants and FGDs shows that from 1992, there was great awareness creation on CSA in the area, and households in the study area started to implement CSA interventions. Therefore, the decrease in deforestation levels from 1995 onwards is linked to the scaling up of CSA activities in the area. During 1985–1995, the size of the agricultural area increased by 3,721 ha; during 1995–2005, it increased by only 11 ha; and thereafter, the size of agricultural land decreased by 506 ha during 2005–2017. This is an indication that from 1995 to 2005, agricultural activities contributed very little to deforestation, while from 2005 to 2017, agriculture did not have any direct contribution to deforestation. Also, it had been noted that during 2005–2017, the size of bushland, forests, and agricultural land was decreasing, while the area for settlements has been increasing. Generally, from 1985 to 2017, the size of forest area and bushland decreased, while agriculture and settlements increased. This is linked to the fact that the study area became the headquarters for the Kilindi District since 2002, and therefore there was an increase in population, which led to high demand for expansion of settlements and increasing crop productivity by improving farming methods but also compensating agricultural areas occupied by settlements.

CONCLUSION

The study revealed that there was rainfall variability, shift in rainfall patterns, and increase in temperature in the study area since 1980's. These changes negatively affected agricultural productivity. This study provides empirical evidence on reduced deforestation and improved farmers' livelihoods due to implemented CSA. It revealed that CSA practices help farmers to withstand climatic stresses while improving their livelihoods by increasing crop productivity and income. This, in turn, improves food security and decreases deforestation. An increase in crop productivity influenced by agroforestry has contributed to an increased income and key livelihoods. The findings also revealed that CSA practices were mostly emphasized from 1992, and its implementation has contributed to the reduction of deforestation levels. Deforestation levels have been reduced from 64.6 ha per year during 1985–1995 to 11.8 ha per year during 1995–2005 and 10.4 ha per year during 2005–2017. Further findings showed that the agricultural area had been decreased from 4,534 ha in 1995 to 4,039 ha in 2017, which is evidence that after the scale-up of CSA from the year 1992, agricultural practices were not contributing much to deforestation. Therefore, agroforestry helped to reduce deforestation levels, especially that caused by farming. We found that adoption of CSA systems such as agroforestry (i.e., agrisilviculture) is very crucial for improving farmer's livelihoods and reducing deforestation. Therefore, farmers need close mentoring on climate-resilient agroforestry systems.

DATA AVAILABILITY STATEMENT

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

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.

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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Explaining the Effect of Crop-Raiding on Food Security of Subsistence Farmers of KwaZulu Natal, South Africa

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Across the globe, crop-raiding has been known to have a significant impact on subsistence farmers livelihoods in developing countries. However, the relationship between crop-raiding and food security of small-scale farmers is not well-studied. We investigated the effects of crop-raiding on homestead food security of a subsistence farming community on the edge of the Hluhluwe Game Reserve in northern KwaZulu-Natal Province, South Africa. We analyzed the relative calories lost to important food security crops (maize, common bean, spinach, and beetroot) damage by crop raiders. In addition, we conducted questionnaire surveys of resident farmers and conservationists of the Hluhluwe Game Reserve to explain the effect of crop-raiding on food security. We firstly assessed how crop loss influenced relative calorie loss as an indicator of food security by comparing relative calorie loss with two predictors of food security: homestead size and contribution of crops to the farmers' food basket. Larger homesteads were more prone to food insecurity as compared to smaller households as they experienced higher calorie loss, especially in terms of maize (*Zea mays*), the most important food security crop in South Africa. This was because maize contributed the highest (91–100%) to the homestead food basket of these farmers. Secondly, we assessed farmers and conservationists' perceptions and opinions on crop-raiding issues. Farmers reported maize as the crop most damaged by crop-raiding animals. Conservationists reported crop-raiding with other major problems in and around the Reserve; this showed that conservationists acknowledge the issue of crop-raiding as a problem for subsistence farming communities abutting protected areas. Both farmers and conservationists reported insects as the most damaging crop raider. Our study suggests that larger homesteads, particularly where maize contributes substantially to homestead food baskets, are more prone to food insecurity in the rural subsistence farming community that we studied. In concordance with many studies, insects were reported as the culprits by both farmers and conservationists. Small, ubiquitous animals, such as insects are reported to cause much crop damage where they occur. The findings of our study suggest that the food security of the studied farmers is threatened by crop-raiding.

Keywords: crop raiding, food security, homestead size, subsistence homesteads, conservationists

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INTRODUCTION

Crop raiding by wildlife, defined as the action of, or results of, wild animals damaging standing crops by feeding on or trampling on them (Hill, 2018), contributes significantly to food insecurity of subsistence homesteads adjacent to protected areas (de Garine-Wichatitsky et al., 2017; Guerbois and Fritz, 2017; Mukeka et al., 2019). Since subsistence homesteads depend mainly on crops they grow for their daily nutrients (Mapiye et al., 2020), a reduction in food supply could even result in starvation in subsistence homesteads (Vanhaute, 2011). In addition, crop raiding by wildlife is at the center of shaping opinions and perceptions of conservationists and farmers abutting protected areas because the frequency and intensity of such raiding will create either positive or negative opinions and perceptions about wildlife and conservation in general (Abdullah et al., 2019; Siljander et al., 2020). The risk of attacks on people also significantly influences perceptions and attitudes toward crop raiding (Anand et al., 2018; Hill, 2018). Such perceptions are notably focused on large species such as elephants (*Loxodonta Africana*) and non-human primates, even when incidences of their raiding are rare (Siljander et al., 2020; Kiffner et al., 2021). Importantly, past studies focused on commercial farmers with little attention on subsistence farmers (Anand et al., 2018; Chen et al., 2019).

The success of conserving biodiversity in protected areas, such as game reserves, depends on the opinions and perceptions of stakeholders of wildlife and conservation, especially of local human communities situated around these areas. Protected areas are reported to be cornerstones for biodiversity conservation (MacKinnon et al., 2020) and are a major means of reducing loss of natural flora and fauna (Schulze et al., 2018). The management of protected areas typically falls to conservationists to protect and manage the needs of wildlife (Matseketsa et al., 2019) while also accommodating the protection of communities around these protected areas. One issue that is of concern to conservationists is human-wildlife conflict experienced by farmers alongside protected areas (Gloriose, 2019). For conservation to be successful, issues that drive conflict such as crop raiding around most conservation areas should also be addressed (Wallach et al., 2018). In this regard, conservation efforts often falter because they fail to fully account for the diversity and multiple levels of human-wildlife conflict in conservation plans and actions (Castaldo-Walsh, 2019). Expanding the scientific knowledge of farmers' perception and opinions of crop raiding behavior is important because such behavior tends to affect the livelihoods of people and can lead to retaliation by farmers (Findlay and Hill, 2021).

In Africa, crop raiding by wildlife is a major influence on subsistence farmers' food baskets (Natukunda, 2019). Subsistence farmers' food basket, also called the farmer's basket, is a customized basket of local agricultural products for daily individual consumption, which is put together by a center of coordination and includes crops from a number of local farms (Rahman and Khan, 2019).

While South Africa may be considered as a food secure country (Zantsi and Bester, 2019), large numbers of subsistence farming homesteads within the country might be food insecure (Zantsi and Bester, 2019; Siphesihle and Lelethu, 2020). We aimed to investigate the effects of crop raiding by wildlife on homestead food security of subsistence farming homesteads adjacent to the Hluhluwe Game Reserve in KwaZulu-Natal Province in South Africa. Food security is defined by Alonso et al. (2018) as the state of having reliable access to a sufficient quantity of affordable, nutritious food, and Wharton (2017) defined subsistence farmers as those farmers who own or manages a farm on which they grow crops or raise livestock sufficient only for their own use, without any surplus for trade.

We investigated food security of subsistence farmers by quantifying the level of damage to four crops, beetroot (*Beta vulgaris*), common bean (*Phaseolus vulgaris*), maize (*Zea mays*), and spinach (*Spinacia oleracea*), which were important food crops to subsistence farming in the area during the study. We first assessed the interaction of factors (crop type and homestead size) known to influence food security (Kaswamila et al., 2007; Bukie et al., 2018) against relative calorie loss due to crop raiding. Traditionally, homestead dietary diversity considers different food groups consumed (Koppmair et al., 2017), and therefore these food groups add diversity in the farmers' diet, for instance maize adds carbohydrates while common beans adds the much-needed protein in the diet of these farmers since meat could be expensive for most marginalized communities.

We also used two separate semi-structured questionnaires, and asked farmers about their crop raiding experiences in order to assess (1) which wildlife species farmers perceived to be a problem, (2) which crops farmers think are raided by these animals, and (3) the percentage that crops add to the farmers' food basket. To assess the attitudes and opinions of conservationists toward crop raiding, we considered three over-arching questions. (1) What issues are a problem in and around the Reserve? (2) Which animals were reported by farmers to raid their crops? (3) Which animal species/type do they consider as most common crop-raiders and are these animals the same as those reported by farmers?

MATERIALS AND METHODS

Study Area

The study was conducted at Phindisweni village (28°26′ S; 31° 09′ E), a subsistence farming community on the edge of the Hluhluwe Game Reserve (28°00′ S; 31°43′ E). Homesteads within the study area comprised the study population. The village was characterized by homesteads with high levels of poverty (Statistics South Africa, 2016). Approximately 86% of the community members depended on crop-based agriculture for their subsistence (Statistics South Africa, 2016). The need for reticulated water, sanitation and electricity were the most pressing issues in the community, with only one homestead reported to have electricity in the 2016 community surveys. These subsistence farms were located on mainly hilly terrain. Like most farming communities abutting protected areas in Africa, this community was affected by crop raiding by wildlife historically (Infield, 1986, 1988) as well as during our study.

Data Collection

We collected questionnaire data from 60 subsistence farmers; however, we used data collected on 20 subsistence farms because of the 2015/2016 declared drought disaster in South Africa. Our study design needed data from active famers as we had to collect damaged crops.

The data from these 20 farms used for this study were as follows: (1) damaged crops of maize, beetroot, common bean, and spinach; (2) farm attributes (farm size; cultivated area size and farm slopes); (3) questionnaire survey data in 60 active and inactive farming households; and (4) questionnaire survey data from 35 conservationists of the Hluhluwe Game Reserve. The FAO maintains that food security involves proper nutrition for a healthy life. Thus, we selected the three variables that served as proxies for food security, including: (1) number of crops damaged of the four important crop types, maize, beetroot, common bean, and spinach, which was quantified by counting the total number of damaged individual crop samples (i.e., leaves of beetroot and spinach and seeds of maize and common bean) in quadrats placed on 20 sampled farms; (2) calorie loss, estimated from the loss of the whole or part of the food plants collected; and (3) contribution of crop types to the homestead food basket (hereafter crop contribution) for statistical analysis. Crop contribution was measured as percentages in five categories ($\leq$30% of food; 31–60%; 61–90%; 91–100%). These variables are reported to influence homestead food security of subsistence farmers (Mugambiwa and Tirivangasi, 2017; Sibhatu and Qaim, 2017; Dodd et al., 2020). Homestead size obtained from questionnaire data, divided into two categories: homesteads with 3–5 people (smaller homesteads) and homesteads with 6–8 people (larger homesteads), were also used as a variable that could influence food security in our study. Indeed, Aidoo et al. (2013) reported household size as one of the determinants of food security in Ghana.

Relative Calorie Loss

To quantify calorie loss, we used a fully automatic e2k combustion oxygen bomb calorimeter (Parr Instrument Company, USA) to obtain calorific values of the collected crop samples. Using the calorimeter, we bombed the dried damaged food crops of maize, common bean, spinach and beetroot to obtain the calorific values, using protocol adapted from Nurdin et al. (2018). The calorific values in kJ/g were recorded and we estimated potential calorie loss by multiplying the calorific values by the proportional level of damage values (obtained by dividing the level of damage for all crops sampled in a farm by the total number of individual crops in a quadrat). For example, the overall potential calorie loss (hereafter Relative calorie loss) for beetroot during the dry season was 862.02 KJ/g, calculated using the proportional level of damage in all farms sampled multiplied by the calorific values obtained in our study, as follows: Relative calorie loss = proportional level of damage* calorific value (kJ/g), so 0.18*4789 KJ/g = 862.02 KJ/g (Raphela, 2019).

For the sake of this study, farm size details were collected as follows: using a Garmin GPSMap62 handheld device, we recorded the geographical location (GPS coordinates of the farms) and elevation of the central position of each of the farms sampled. The area of each farm and the area cultivated were established by walking the perimeter of each sampled farm and cultivated land separately and calculating the area of each in m^2. The distance between each farm and the reserve boundary was determined by a straight-line shortest distance from the center of the farms to the reserve boundary fence using ArcMap (ArcGIS, V10.3, software package, ESRI).

Questionnaire Surveys

Interviews are the most effective way to obtain detailed individual opinions and perceptions about an issue. Nonetheless, we are aware that interview-based approaches suffer from biases such as the researcher leading the respondent, respondent anticipation to please the researcher, pushing for concise answers (Alonso and Moscoso, 2017), or discrepancies between what people report and what they actually feel or do (Yan et al., 2020). These weaknesses of the interviews were accounted for in the information sheet and consent forms for both farmers and conservationists by clearly stating that the research was for educational purposes and there would be no compensation for participating and that the potential participants were free to withdraw from the study at any time. Interviews were conducted in English and/or IsiZulu (the local language) for conservationists and in IsiZulu only for the farmers and, only if they agreed, did the interview proceed. The purpose of the survey was explained to the potential interviewee. The identity of all respondents remained anonymous during this study as outlined in the conditions of our ethics permit.

We gathered signed consent forms from each respondent to participate in the study before conducting each survey. Permission to collect data was sought from the University of the Witwatersrand Human Ethics Committee (protocol number H15/11/29) and from the Ezemvelo KZN Wildlife permits office (protocol number P27/2015) and verbal permission to collect data from the community was received from the community chief. The purpose of the survey was explained to the chief and the potential interviewees. Each interviewee was informed that sensitive information and personal characteristics would not be included in any reports without their consent. In addition, an information sheet with information about the research details was also read out to the interviewees. The questions were both closed and open-ended and were aimed at extracting the respondent's opinion on crop raiding by wildlife in neighboring subsistence farms. All respondents interviewed were adults over 18 years of age. The questionnaires, adapted from Seoraj-Pillai and Pillay (2017), were administered with the help of two local research assistants from March 2016 to May 2016.

Farmer's Questionnaires

We administered 60 semi-structured questionnaires to 60 different farmers, However, we only used 20 questionnaires where farmers were active and had important targeted crops for this study for data analysis. We trained the research assistants about the survey protocol, and they were also given color photographs of wildlife in the Hluhluwe Game Reserve with names in English and isiZulu to assist respondents in identifying crop raiding species. We used a stratified sampling approach to sample the farming homestead. We selected every second homestead for the interview. The selection of the homesteads was done in such a way that the homesteads were located a maximum of 6 km from the reserve boundary. A frequency distribution of distances of farms from the reserve boundary generated a bimodal distribution between farms <3 km and those >3 km. We therefore designated farms 1–3 km of the reserve boundary as near and farms 4–6 km as further from the reserve. We restricted the survey to one respondent per homestead to avoid pseudo-replication of results. An average of 7 interviews took place per day throughout data collection phase.

Conservationist's Surveys

Surveys were limited to conservationists in the Hluhluwe Section of the Hluhluwe iMfolozi Park (HiP). We administered 35 semi-structured questionnaires to 35 conservationists. The questionnaire was divided into three sections, including demographic information, perceptions and opinions of crop raiding by wildlife, and interactions of conservationists with neighboring farming communities. The perception and opinion questions considered whether conservationists knew about conflicts in and around the reserve and reports of crop raiding animals by farmers. Respondents who answered "yes" to these questions were asked supplementary questions about the animal species that were reported and also animals they thought raided crops of adjacent farmers. The survey took place over 3 months from March 2016 to May 2016. Questionnaire interviews were administered at the Hluhluwe Game Reserve research center.

Statistical Analysis

We first analyzed the relationships between Relative calorie loss and several predictors and their interactions (crop type, homestead size, and crop contribution) to assess the link between the interaction of these predictors and food security by running a series of Generalized linear models (GLM) to find the best fit model. These analyses considered between farm variations to assess whether any of the predictors could be considered for food insecurity. The GLMs were run using the *glm* function with a Poisson distribution and Logit link function (lme4 package, Bates et al., 2015). The Relative calorie loss was analyzed as a response variable for all GLMs performed. For all models, we included farm size as a covariate to account for the potential farm size effect. We checked the model fit for the variables described above and used the most appropriate model based on the plot of the residuals against the fitted values from each model. For all models, significance was determined using Wald (χ^2) statistics and *P*-values were generated by running the Anova of the model (Bates et al., 2015). Next, we applied Spearman rank analysis to assess the relationship between number of crops lost and Relative calorie loss to assess potential food insecurity. We further applied a series of separate GLMMs fitted *via* maximum likelihood with a glmer function and a binomial distribution (reported and not reported answers) to ascertain the farmers' perceptions and opinions on crop raiding. Lastly, we ran Chi-squared tests (χ^2) of independence to analyze whether there were differences between the conservationists' responses to the opinion and perception questions asked. All graphs were produced using a GGplot2 package from the R software.

RESULTS

Relative Calorie Loss

We presented the model with 3-way interaction as it was the best fit with an AIC value of 13,449 as compared to the other models. There were significant differences found for all crop types, crop contribution, the interaction between all crop types and household size, the interaction between all crop types and crop contribution, the interaction between household size and crop contribution and the three-way interaction between crop type-maize, household size and crop contribution (**Table 1**). However, there was no significant difference between household size, the interaction between crop type common bean and household size, the three-way interaction between crop type-common bean, household size and crop contribution and the three-way interaction between crop type-spinach, household size and crop contribution (**Table 1**). Farm size was also a significant predictor of the relative calorie loss (**Table 1**).

Significantly higher calorie losses were: (1) in larger homesteads as compared to smaller households; (2) for maize across household size; and (3) in larger households across all crop types, except for spinach, with maize reported as contributing more to larger households' food basket (91–100%) as compared to other food crops (**Figure 1**). Common bean was the second food crop with the highest relative calorie loss across the household size with inconsistent reports by farmers about the contribution of common bean to household food basket between the households, but farmers from larger households where Relative calorie loss was calculated to be high for common bean also reported the highest crop contribution of this crop (**Figure 1**). The Spearman rank correlation showed a negative statistically significant relationship between Relative calorie loss and number of crops lost ($r_s = -0.55$; $P < 0.001$).

Farmers and Conservationists' Perceptions About Crop Raiding

We analyzed farmers, and conservationists' responses to major questions pertinent to this study as detailed below.

Problems in and Around the Reserve

We asked conservationists whether they knew of any anthropogenic and crop-raiding problems in and around the reserve. Only one conservationist out of 35 did not know of any problems/issues in and around the reserve, which was significantly different to chance ($\chi^2 = 31$, df $= 1$, $P < 0.001$). We further asked which problems/issues they knew about in and around the reserve from a list of possible problems. Of the 34 respondents who reported problems, 15 (41%) indicated collection of fuelwood by the local communities, 30 (88%) indicated crop raiding by wildlife and domestic live-stock, 7 (20%) indicated cutting of trees by the local communities, 31 (91%) diseases, 13 (38%) fires and grazing by domestic live-stock, 34 (97%) hunting by the local communities, 32 (94%) indicated poaching and 1 (3%) indicated trespassing (**Figure 2**).

There were significant differences in the number issues/problems and those that were not reported by conservationists for crop raiding, cutting trees, diseases, hunting,

TABLE 1 | Output of a GLM model showing crop types damaged, crop contribution, household size and their interactions with farm size as a covariate for relative calorie loss.

Variables	Estimate	Std. error	*Z*-value	*P*-value
Crop type_beetroot	**2.967**	**0.355**	**8.341**	***P*** **< 0.001**
Crop type_common bean	**5.760**	**0.278**	**7.090**	***P*** **< 0.001**
Crop type_maize	**6.552**	**0.139**	**46.848**	***P*** **< 0.001**
Crop type_spinach	**7.078**	**0.954**	**74.163**	***P*** **< 0.001**
Household size	0.040	0.057	0.709	*P* = 0.478
Crop contribution	**0.208**	**0.997**	**2.134**	***P*** **= 0.032**
Farm size	**0.000**	**0.000**	**−6.603**	***P*** **< 0.001**
Crop type_common bean: household size	0.140	0.073	1.909	*P* = 0.056
Crop type_maize: household size	**−0.246**	**0.062**	**−3.964**	***P*** **< 0.001**
Crop type_spinach: household size	**−0.199**	**0.059**	**−3.332**	***P*** **< 0.000**
Crop type_common bean: crop contribution	**0.769**	**0.121**	**6.329**	***P*** **< 0.001**
Crop type_maize: crop contribution	**−0.594**	**0.105**	**−5.649**	***P*** **< 0.001**
Crop type_spinach: crop contribution	**−0.386**	**0.101**	**−3.825**	***P*** **< 0.001**
Household size: crop contribution	**−0.413**	**0.016**	**−0.256**	***P*** **= 0.000**
Crop type_common bean: household size: crop contribution	−0.085	0.020	−4.196	*P* = 0.797
Crop type_maize: household size: crop contribution	**0.072**	**0.017**	**4.162**	***P*** **< 0.001**
Crop type_spinach: household size: crop contribution	0.288	0.016	1.715	*P* = 0.086

Significant values are shown in bold.

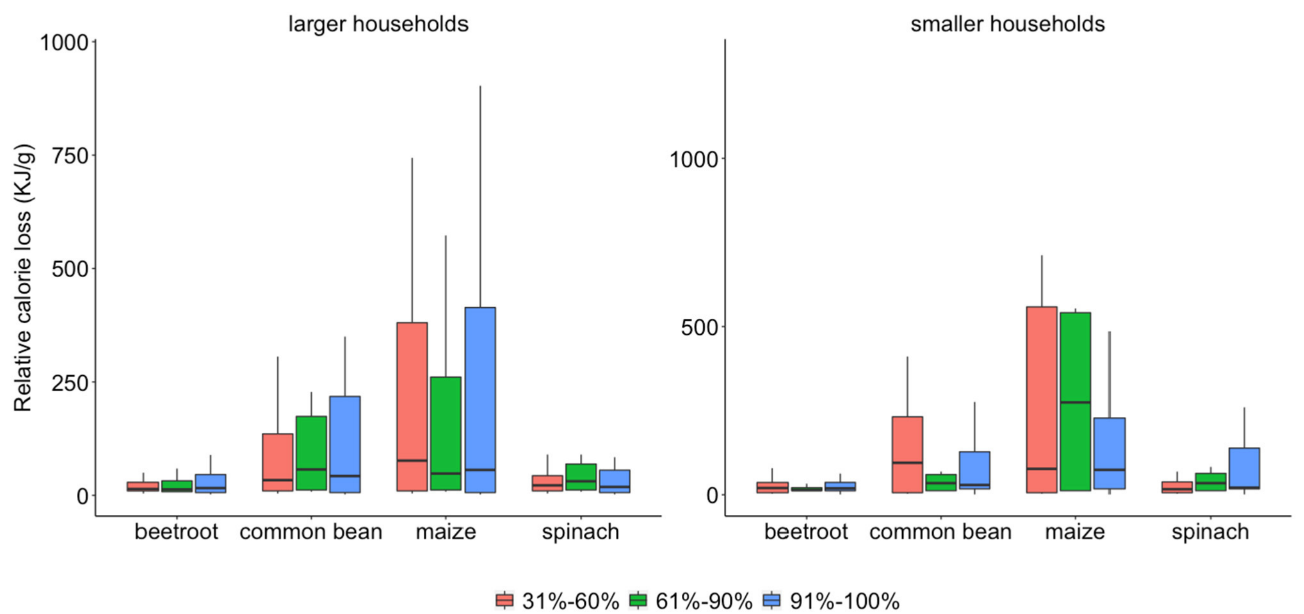

FIGURE 1 | Relative calorie loss by homestead size*crop type*crop contribution (three-way interaction) experienced by subsistence farmers on the edge of Hluhluwe Game Reserve, South Africa. Boxes show medians (solid black line across the box) and 1st (top box) and 3rd (bottom box) quartiles. Whiskers shows confidence limits. Food basket is the number percentage that farmers reported the sampled crops contribute to their household food basket.

poaching, and trespassing whereas no significant differences were found in conservationists' responses for collection of fuelwood, fires and grazing (**Figure 2**).

Crop Types Raided

Farmers near and further away from the reserve reported banana (*Musa paradisiaca*), beetroot (*Beta vulgaris*), butternut (*Cucurbita moschata*), cabbage (*Brassica oleracea var. capitata*), common bean (*Phaseolus vulgaris*), guava (*Psidium guajava*), maize (*Zea mays*), mango (*Mangifera indica*), orange (*Citrus aurantium*), peach (*Prunus persica*), potato (*Solanum tuberosum*), pumpkin (*Cucurbita pepo*), spinach (*Spinacia oleraceae*), sweet potato (*Ipomoea batatas*), and yam (*Colocasia esculenta*), as crops raided on their farms (**Figure 3**).

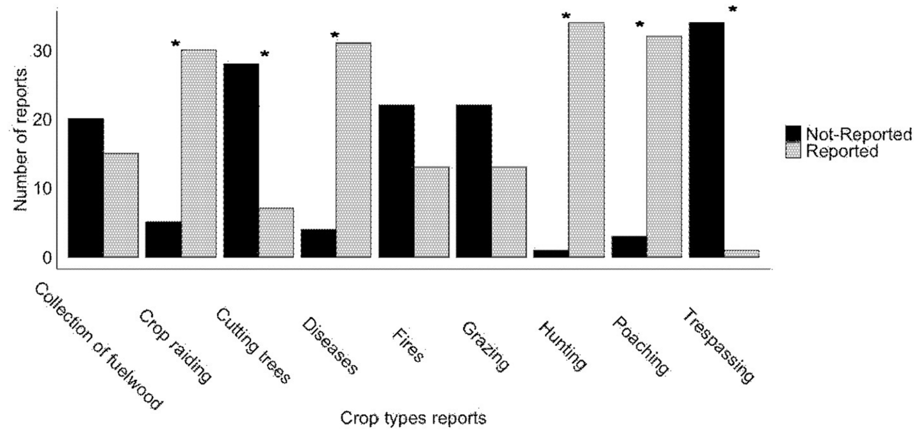

FIGURE 2 | The number of conservationists that did and did not report issues/problems concerning the local farming communities at the edge of the Hluhluwe Game Reserve boundary, South Africa. Asterisks above bars show significant differences between conservationists that reported issue/problem vs. those that did not report those issue/problem.

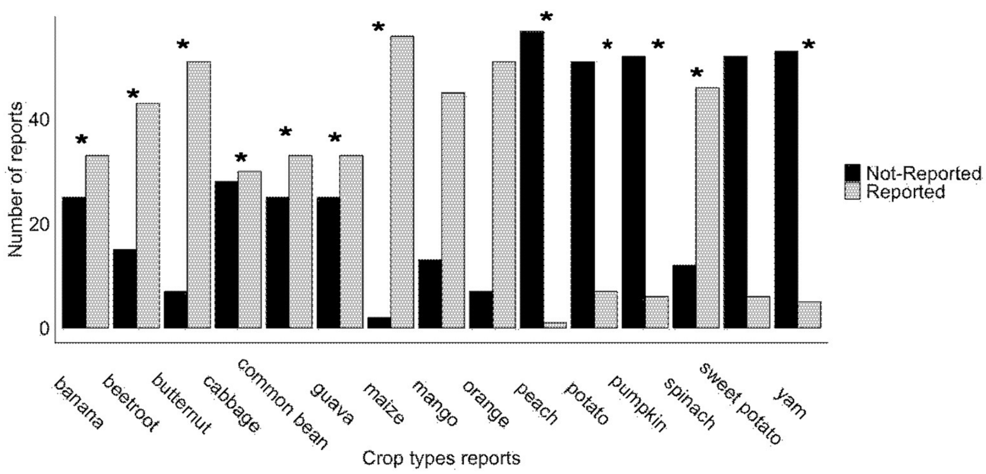

FIGURE 3 | The number of farmers that did and did not report raiding of different crop types at the edge of the Hluhluwe Game Reserve boundary, South Africa. Asterisks above bars show significant difference between farmers that reported a particular crop type was raided vs. those that did not report that crop type.

Crop raiding reports were significantly affected by crop type [Wald $\chi^2_{(14)} = 105.92$, $P < 0.001$] and the interaction between crop type and distance of farms from the reserve [Wald $\chi^2_{(14)} = 29.26$, $P = 0.009$]. Significantly higher number of farmers reported that maize (*Zea mays*) was mostly damaged compared to all the other crop types and significant differences were found between farmers' responses for banana, beetroot, butternut, cabbage, common bean, guava, maize, peach, potato, pumpkin, spinach, and yam, whereas no significant differences were found between farmers, responses for mango, orange, and sweet potato (**Figure 3**).

Crop Raiding Animals

We asked both farmers and conservationists about animals that raid their crops or that they thought raid crops. Farmers mentioned more animals are compared to conservationists (**Figures 4A,B**). However, significantly higher numbers of farmers and conservationists reported crop raiding by insects as compared to all other crop raiding animals (**Figures 4A,B**). Reports of crop raiding by farmers were significantly affected by crop raiding animal type [Wald $\chi^2_{(12)} = 87.76$, $P < 0.001$] and the interaction between animal type and farm distance from the reserve [Wald $\chi^2_{(12)} = 23.13$, $P = 0.026$], but there was no significant effect for the farm distance to the reserve boundary [Wald $\chi^2_{(1)} = 0.36$, $P = 0.544$]. Significant differences were found between farmers' responses for all reported animals except for free living birds and vervet monkey (**Figure 4A**).

In total, 31 of 35 conservationists (88%) reported crop raiding animals and 4 of the conservationists did not respond to this question and there were significant differences between the responses ($\chi^2 = 17$, df = 1, $P < 0.001$). There were significant differences in the number of conservationist's responses for all

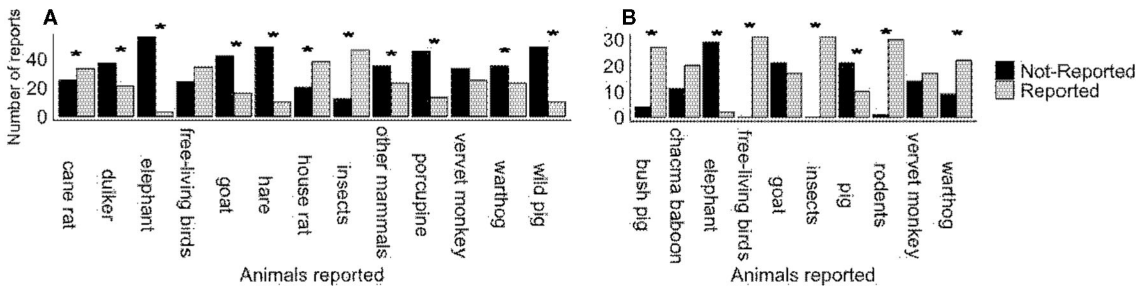

FIGURE 4 | The number of farmers **(A)** and conservationists **(B)** that did and did not report crop raiding animals and potential crop raiding animals, respectively, at the edge of the Hluhluwe Game Reserve boundary, South Africa. Asterisks above bars show significant differences between reports of a crop raiding animal type vs. those that did not report that animal type.

animals reported except for chacma baboon (*Papio ursinus*), domestic goat, and vervet monkey (**Figure 4B**).

To follow-up on crop raiding animals in order to ascertain real and perceived crop raiding animals before linking these animals to exacerbation of food insecurity, conservationists were asked which animals do farmers report as crop raiders. Bush pig (*Potamochoerus larvatus*), warthog (*Phacochoerus africanus*), vervet monkey (*Chlorocebus pygerythrus*) and porcupine (*Hystrix africaeaustralis*), elephant (*Loxodonta africana*) were reported by conservationists as culprits similar to farmers reports, even though farmers reported more crop raiding animals than conservationists (**Table 2** and **Figure 4B**). Significant differences were found between farmers, reports for African wild dog (*Lycaon pictus*), elephant, lion (*Panthera leo*), vervet monkey, and warthog (**Table 2**).

DISCUSSION

Several factors such as food crops, household size, crops contribution to household food basket and crop raiding animals can be linked to household food insecurity of subsistence farmers (Nyirenda et al., 2018; Dodd et al., 2020). In Eastern Zambia, Nyirenda et al. (2018) showed how crop raiding elephants of Lupande Game Management Area affected the food security of the neighboring subsistence farmers. In Hungary, Dodd et al. (2020) reported larger households that do not grow maize and beans to be more likely to experience insufficient food.

Here we investigated how crop raiding by wildlife affects food security of subsistence households adjacent to the Hluhluwe Game Reserve, South Africa. We assessed the perceptions and opinions of farmers on the edge of the Hluhluwe Game Reserve boundary and conservationists employed in different positions by the Reserve on crop raiding issues that could lead to food insecurity.

As a guideline for food security, the World Health Organization (2020) maintained that people's diets must meet the requirements for a healthy life. We investigated the potential calories lost by crop types raided, household size, crops contribution to farmers' food basket, and found that larger households experienced higher relative calorie loss compared to smaller households, particularly for maize. This finding could see these farmers transition from being food secure to being food insecure rapidly. A study in Honduras has shown that larger subsistence farming households, especially those that do not grow maize and beans as their staple foods, are more likely to experience insufficient food compared to individuals from wealthier and smaller households (Dodd et al., 2020). Following the definition of food security by the (Food and Agricultural Organization (FAO), 2010), this finding implies that larger households were more prone to food insecurity compared to smaller households. In many African societies, maize is a preferred food crop because it provides a higher yield for lower input of labor (Silva et al., 2019). Thus, maize is a staple and food security crop in South Africa (Sinyolo, 2020). Maize also provides at least 30% of the food calories for more than 4.5 billion people in 94 developing countries and contributes to over 20% of food calories in parts of Africa and Asia [Food and Agricultural Organization (FAO), 2016]. In addition, maize is also a key indicator in the assessment of food security in most developing countries since it is important to the poor as a means of overcoming hunger (Lopez-Ridaura et al., 2019), yet the nutritional value of maize makes it more vulnerable to raiders such as primates (Siljander et al., 2020).

In North-eastern Tanzania, crop raiding by wildlife was reported to have reduced maize yields that could sustain a family up to 11 months per year (Kaswamila et al., 2007). We found that the highest relative calorie loss occurred in households where maize contributed the highest (91–100%) to the farmers food basket, implying that these households were more prone to food insecurity as compared to households where food crops contribute less to the household food basket.

We also found that farm size was a significant predictor of Relative calorie loss and the number of crops lost predicted Relative calories loss, indicating that potential calorie loss is coupled with crop loss and the size of the farms in our study. The more subsistence farmers in our study lose crops, the more likely they are to become vulnerable to food insecurity because of the relationship between calories lost and the number of crops lost found in our study. Indeed, the size of the farms will also determine food security as subsistence farmers that cultivated a large portion of their farm can have some food crops left after

TABLE 2 | Results of Chi-squared statistics analysing the responses of conservationists to the question "which animals do communities report to the Reserve as crop raiders?"

Question	Animals	Chi-squared statistics		
		χ^2	*Df*	*P*-value
Which animals do neighboring communities report crop-raiding?	African wild dog	**7.08**	**1**	**<0.001**
	Bush pig	16.2	1	0.081
	Chacma baboon	0.8	1	0.371
	Elephant	**12.8**	**1**	**<0.001**
	Lion	**7.2**	**1**	**0.007**
	Porcupine	0.8	1	0.371
	Vervet monkey	**9.7**	**1**	**0.371**
	Warthog	**12.8**	**1**	**0.000**

Significant values are shown in bold, and animals reported by both farmers and conservationists are italicised.

extensive raids. This further implies that should crop raiding persist in our study area, the farming homesteads, especially larger homesteads which cultivated smaller areas, will become more susceptible to food insecurity.

Farmers and conservationists reported incidences of crop raiding on the edge of the Hluhluwe Game Reserve boundary. Conservationists did not answer the question of crop types raided, as an important food security predictor (Dodd et al., 2020), but conservationists did confirm that crop raiding is the third highest problem experienced by farmers adjacent to the reserve (See **Figure 2**). Nevertheless, farmers reported a range of important food security crops being targeted by crop raiding animals (see **Figure 3**). Consistent with other human-wildlife conflict studies (Adeola et al., 2018; Alemayehu and Tekalign, 2020; Siljander et al., 2020), farmers reported that maize was the most damaged by crop raiding animals. Adeola et al. (2018) found that maize was the most commonly ranked crop of seasonal harvest that was lost to primates raiding around Kainji Lake National Park in Nigeria. In Kenya, Long et al. (2020) found that maize made up 55% of the cases reported in relation to human-wildlife conflict. Maize is the food crop favored above other crops by people and crop-raiding herbivores and omnivores (Alemayehu and Tekalign, 2020) and most of the studied households rely on subsistence farming as their main livelihood. Therefore, crop-raiding, especially of the most recognized staples, is a serious threat to their food security.

Singh et al. (2017) and Smith et al. (2018) reported that the crops people consider to be vital to their subsistence are also the crops they perceive to be most vulnerable to damage from wild animals. Maize has been identified as a frequently raided crop in many studies (Adeola et al., 2018; Alemayehu and Tekalign, 2020; Long et al., 2020) and our study through experiments and perceptions of farmers and conservationists provides an assessment of the vulnerability of this important food security crop to crop-raiding.

Both farmers and conservationists reported that smaller, more ubiquitous and more persistent animals (i.e. insects and free-living birds) as the most important crop raiders outside the reserve, but insects were reported by the highest number of farmers and conservationists as the number one crop raider in our study, consistent with other studies in Africa (Yeheyes and Abebaw, 2017; Deutsch et al., 2018). Deutsch et al. (2018) reported insect pests to substantially reduce yields of three staple grains, rice, maize, and wheat, which are also reported food security crops in most African subsistence homesteads. Many studies in Africa reported insects as one of the major problems in agricultural land (Yeheyes and Abebaw, 2017; Deutsch et al., 2018; Okonya et al., 2019) and the damage they cause is always reported as widespread (Dively et al., 2018). However, conflict, drought, and insects have all been leading concerns for African food security in recent years[1]. Worst is that our study took place during the 2015/2016 drought season in South Africa. Therefore, the vulnerability of our study community to food insecurity was escalated during the study. Insects were also reported with other determinants of household food security with annual mean loss of 2687.6 Ethiopian Birr in households in the Omo-nada district in South Western Ethiopia (Yeheyes and Abebaw, 2017). This shows how insects as crop raiders can adversely affects the rural household food security. In Rwanda and Burundi, Okonya et al. (2019) found that insects caused widespread damage to crops, leaving the subsistence farmers vulnerable to food insecurity.

CONCLUSION

We investigated the impact of crop raiding by wildlife on food security of subsistence farmers on the edge of the Hluhluwe Game Reserve. Our study was the first to consider human-wildlife conflict in marginalized rural communities by directly measuring the impact of wildlife and by soliciting the views and opinions of subsistence farmers and conservationists in South Africa simultaneously. Specifically, we found that insects frequently depredated staple food security crops (maize) and other crops. Moreover, we found that larger homesteads and small farms were more prone to food insecurity because of crop raiding. However, the crop raiding animals and the level of damage recorded would have been unlikely to cause food

[1]Anderson, W., Taylor, C., McDermid, S. P., Ilboudo-Nébié, E., Seager, R., Schlenker, W., et al. (under review). Characterizing the effect of drought, conflict, and locusts on food security in Africa. doi: 10.21203/rs.3.rs-104065/v1.

insecurity in the studied homesteads. Thus, our study indicates potential but not actual food insecurity because of crop raiding. The food security of the studied farmers during the study was threatened by damage caused by insects coupled with the prevailing drought. The loss of food crops, in particular maize crops, due to crop raiding could exacerbate the farmers plight, leading to food insecurity.

An important finding of our study was consistency between conservationists and farmers on crop raiding animals reported. Conservationists also reported crop raiding was a major problem in and around the Reserve, which showed that they acknowledge the issue of crop raiding as a problem for subsistence farming communities.

Recommendations

Our study suggests several areas of future research. (1) There is a need for a long-term study of the Phindisweni community to cover many seasons over several years. This will provide an important comparison with the data obtained in our study, which was conducted during a drought. (2) Other proxies of loss of crop raiding, such as crop yield, need to be considered. Although we attempted to quantify nutritional loss of crop parts through their damage, crop yield prior to and after damage was not known because farmers did not keep crop yield information (pre-and post-harvest) during the prevailing drought. Studies around Africa and India have investigated loss based on crop yield (Sekhar, 1998; Mackenzie and Ahabyona, 2012). In India, near the Tiger Reserve, Sekhar (1998) found that the crop yield was ∼30–35% more than when there was no major damage. Around the Kibale National Park in Uganda, Mackenzie and Ahabyona (2012) reported 20% loss of crops due to crop raiding compared to the crop yield without damage in the previous 6 months. (3) Future investigations should incorporate more detailed nutritional analyses of cultivated foods consumed at different times of the year, and patterns and changes over longer periods of time. Sampling might have to be done opportunistically since crop raiding can be unpredictable, depending on a particular set of environmental conditions (e.g., high rainfall, high crop yields, and ease of accessibility of wildlife to crops). (4) We suggest that prospective studies incorporate a mixture of analytical methods to quantify food security, such as including questionnaire interviews that ask farmers about the food they consumed to quantify food security using dietary diversity. Such methods would be critical in evaluating how food crops contribute to the homestead food basket (Hill, 2000). (5) Although our study has shown that crop raiding is a challenge for the farmers, we do not have data about how they can mitigate against food insecurity should this arise. (6) Finally, we also need studies in other parts of South Africa, especially where subsistence farmers abut protected areas with different environmental conditions, to assess whether our findings are generalizable across South Africa. Most importantly, we strongly recommend that farmers focus more on mitigation strategies that will address crop raiding by insects, free living birds and rodents as they were the most reported crop raiders. Also, maize as the most damaged and raided food security crop, should be given priority when mitigation measures are implemented.

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's' Human (HREC) (non-medical) under protocol number H15/11/29. The participants provided their written informed consent to participate in this study. The animal study was reviewed and approved by University of Witwatersrand Animal Ethics Screening Committee (2015/08/37/B).

AUTHOR CONTRIBUTIONS

TR and NP conceived and designed the study, research, work, and analyzed the data. TR collected the data and led the drafting of the manuscript. All authors contributed critical, intellectual content to the drafts, and gave final approval of the version to be published.

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Steering the Nexus: iZindaba Zokudla and Governing for Sustainability

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"iZindaba Zokudla" means we talk about the food that we eat. iZindaba Zokudla is a public innovation lab that uses stakeholder-engagement methods to create "opportunities for urban agriculture in a sustainable food system." iZindaba Zokudla is presented as an extra-institutional means to govern the water, land, energy, and waste nexus. This reflective essay critically describes iZindaba Zokudla and applies this to the design of institutional steering mechanisms to govern the food, water, land, and energy nexus towards sustainability. Governance is an intersubjective and interactive process between the subjects of governance and governance itself. Sustainability, as an interactive process, implies the creation of autocatalytic and symbiotic communities in society that integrates diverse actors and stakeholders, inclusive of scientific and lay actors, and ecosystems. iZindaba Zokudla is a means to govern and create such communities, and this article describes and reflects on how iZindaba Zokudla has created and managed such symbiotic communities or autocatalytic networks in the food system. The article generalises how the activities conducted in iZindaba Zokudla can be used to govern the water, land, energy, and waste nexus for sustainability. The article shows how iZindaba Zokudla has realised a progressive governance through the facilitation of its Farmers' Lab and website; how it has created opportunities for participation; and how it enables critical reflection in society.

Keywords: stakeholder engagement (SE), governance (ESG), communities of practise (COP), agriculture transformation, public innovation lab

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INTRODUCTION: IZINDABA ZOKUDLA AS EXTRA-INSTITUTIONAL GOVERNANCE

iZindaba Zokudla[1] is a multi-stakeholder engagement project that aims to create opportunities for urban agriculture in a sustainable food system. iZindaba Zokudla emerged from a research project in participatory technology design (Malan and Campbell, 2014; Campbell and Malan, 2018; Malan, 2020a). The NGOs REOS Partners and TransForum (REOS Partners, and TransForum, 2011) and the South African Food Lab introduced the author to food systems thinking and TransForum's multi-stakeholder engagement methodology accommodating public, business, and civil society interests (Regeer et al., 2011; Van Latesteijn and Andeweg, 2011). TransForum's approach is to build sustainable business by linking with "all relevant stakeholders" (Regeer et al., 2011: 27). These small teams include entrepreneurs, welfare, and public sector representatives, a process monitor, and other stakeholders. iZindaba Zokudla follows this, albeit by mobilising stakeholders in a social

[1] In isiZulu this correctly means "the court of the Chief where we discuss the food that we eat together."

lab (Hassan, 2014) as an open participatory event (the Farmers' Lab) wherefrom groups may be mobilised for enterprise creation and activism in the food system.

The water, land, energy, and waste nexus (hereafter "the nexus") overlaps with the food system. A sustainable food system will transform the current system and manage it within its biological and physical limits, and the regenerative potential inherent in its resources. The trade of food by "enterprises" however creates opportunities for sustainability as enterprises can innovate and develop sustainable products and services. Economic activity and businesses are "brokers between producers and consumers [that can] create new socio-ecological relations" (Pereira et al., 2020: 1327) and these "Entrepreneuring" (Bruton et al., 2013; Tobias et al., 2013; Lynde, 2020) or "institutional entrepreneurship" (Sidibé et al., 2018: 95) or "infrastructuring" (Nogueira et al., 2020) opportunities are a form of governance that can create sustainable enterprises and transform the food system. iZindaba Zokudla is an open, voluntary forum located in academia and civil society that aims at creating enterprises based-on new relationships between actor-entrepreneurs/activists (those who act) and stakeholders, who have an interest in the sustainability of such enterprises.

iZindaba Zokudla contributes to sustainability by creating opportunities for public deliberation on a sustainable food system. This manages and governs the system, but the Lab attracts actors and stakeholders with a clear interest in a low external input agriculture (Malan, 2015: 55). These deliberative choices influence others, and creates overarching narratives for action, and this has moved many towards collaborating and adopting sustainable practises. This article distils the experience of the "convener" of this forum to identify how such a forum or social lab can help govern the water, land, energy and waste nexus towards sustainability.

The author hosted a series of workshops in 2013 to "embed" the participatory technology design project in the local community in Soweto, Johannesburg. This "assembly" led to the creation of iZindaba Zokudla and the Farmers' Lab and aimed at creating a strategic plan for urban agriculture in Soweto, Johannesburg (Malan, 2015). iZindaba Zokudla's Farmers' Lab should be understood as a form of a "public innovation lab" (McGann et al., 2018, 2019) or a "social lab" (Hassan, 2014) that uses social methodologies, and now digital methods (Williamson, 2015) to achieve its ends.

iZindaba Zokudla's Farmers' Lab (The "Lab") has amongst others instituted a system of referral and facilitation to key entities in the University of Johannesburg, civil society, state, and business that assist emerging entrepreneurs. On the 13th of May 2017 it hosted activists from the African Centre for Biodiversity, The Department of Agriculture Forestry and Fisheries and Bioversity International that discussed the creation of seed libraries. Later, on the 5th of August 2017, a leading activist used the Lab to organise farmers to participate in a public information session organised by Parliament on new seed Bills (Rousell, 2017). This assisted a submission to Parliament on the Bills, but two aspects of this organising deserve mention. The activist mentioned later formed an agricultural incubator with other activists and entrepreneurs (which is linked to the activities of iZindaba Zokudla) and another farmer arrived at the Farmers' Lab on the 19th of August 2017 with more than 30 different kinds of indigenous seeds that he catalogues in a seed library, which forms part of his farming enterprise. These actors created sustainable activities with, through and alongside iZindaba Zokudla, and this is described in this article.

The methods used in the Lab enables local actors to coalesce and draw on the opportunities and resources amongst themselves (Malan, 2020c). The Lab is an "omnibus" event that lowers the opportunity cost of pitching and developing a new enterprise, facilitates access to farmers for researchers and business incubators, and allows farmers to network and build relationships with a broad range of stakeholders, including activists, and *vice-versa*. The Lab has also facilitated the "launch" of both the Khula! app (http://www.khula.co.za/) and the uptake of aparate.co. amongst farmers in Soweto. iZindaba Zokudla hosted the Slow Food Soweto Eat-Ins (see Malan, 2020c), food festivals that vividly and publicly illustrate the viability of a sustainable food system. The Lab was active from the 16th of May, 2015, until the 14th of March, 2020 when Covid-19 regulations temporarily prohibited face-to-face gatherings. The last workshop attracted more than 400 participants, and tested financial products for new and small-holder farmers, and indigenous vegetables and seeds, amongst others[2]. During 2020 preparatory work was done to build the iZindabazokudla.com website as digital means to manage virtual "Communities of Practise" as an entrepreneurship development strategy (Wenger, 1998; Malan and van der Walt, 2019) that is only briefly described in this article.

GOVERNANCE IN A PUBLIC INNOVATION LAB

Ostrom (1990) reminds us that actors in common-property regimes develop "shared norms and patterns of reciprocity" and "social capital with which they can build institutional arrangements" (1990: 184) to govern the commons. Existing institutional structures however, are (constantly) transformed by the supply of new institutional arrangements. This "competitive" supply of new arrangements leads the development of new institutional and governance regimes which is key in successful governance.

Social labs create "infrastructuring" (Nogueira et al., 2020), architecting (Lynde, 2020: 3) or "structuration" (Gebreyes, 2018: 130) opportunities to renegotiate the structures wherein action takes place, akin to the development of new governance arrangements. iZindaba Zokudla, as a "social lab," enables actors and stakeholders to shape systems and incorporate diverse influences in the food system as they realise their own projects. Nogueira et al. (2020: 3) emphasise that "… infrastructures carry a system of offerings (e.g., people, objects, environments, messages, and services) and affordances that standardise the circulation and allocation of resources, as well as how the infrastructure is used." They emphasise that a public innovation

[2]See: https://www.facebook.com/IzindabaZokudla/posts/2593612467524472.

lab offers an opportunity to renegotiate and "democratise the processes of determining how resources should be allocated and mobilised" and change what these "offerings afford users to do."

The opportunity to "infrastructure" society or governance creates an interactive and subjective relationship between actors and stakeholders. As they structure or "infrastructure" systems, enterprises, products, and governance arrangements, they themselves get shaped by these very same arrangements. This occurs in a very peculiar way in a public innovation lab. A "public innovation lab" is "an experimental R&D lab for social and public problems, located in the interstitial borderlands between sectors, fields, and disciplinary methodologies" (Williamson, 2015: 256). A public innovation lab is important as it can produce "new methods for making sense of social phenomena … redefining the way the … world works, designing methods to measure it, and producing policy products and recommendations to modify it" (Williamson, 2015: 267).

A public innovation lab creates the subject of governance in a very peculiar way. A "Lab" shapes subjects to become "governable participants in emerging strategies, techniques, and methods of digital governance" (Williamson, 2015: 267). iZindaba Zokudla influences governance through the creation of subjects of governance—or entrepreneurs who influence the food system through their activities in the market. An intersubjective conception of governance allows us to understand how actors outside structures of power and in society influence governance itself. Below we examine what is at stake when governance is intersubjective.

GOVERNANCE AS INTERSUBJECTIVE

Intersubjectivity stands in some contrast to a hard—command and control—conception of governance. The South African King IV report (IoD, 2016) warns against following such "mindless rules" (2016: 36). It invites intersubjectivity (IoD, 2016: 4) as a "stakeholder-inclusive" approach, that is a "party to all sources of value" created "for itself, and others" (2016: 25). Significantly, it proposes "Sustainability" as "an interdependent relationship between the organisation and its stakeholders, and the organisation's ability to create value for itself depends on its ability to create value for others" (IoD, 2016: 23).

The philosophical history of governance as an intersubjective endeavour is reconstructed by Thomas Lemke from published interviews of the philosopher Michel Foucault (1926–1984). Governance and "governmentality"—as governing "self and others"—stems from constitutionalism and the demise of the old European feudal system. New states determined, and was determined by, the creation of a new "subject" of the state, the citizen. Governance is tied up with "the modern sovereign state and the modern autonomous individual [who] co-determine each other's emergence" (Lemke, 2007: 44, Lemke, 2000: 3). "Hence we can speak of the economy as an open economic domain that is created only by incessant social intervention" (Lemke, 2000: 196). Governance consequently begs the question of "the conditions of a consensus or the prerequisites of acceptance" (Lemke, 2002: 54).

When we govern and are governed, we may acquiesce or innovate. Governance allows actors opportunities to constantly re-negotiate, with others, the activities they are performing. The idea of "infrastructuring" as means to re-create systems, opportunities and current paths of activity converges with an intersubjective governance. A public innovation lab creates the conditions for such "infrastructuring" to take place. The effects of this are clearly felt outside the lab, in society, and in the changed behaviour of actors and systems.

GOVERNANCE AS "INFRASTRUCTURING"

In South Africa the background contours of the market are shaped not completely by free-market principles, but also by an affirmative and race-based strategy (Broad-Based Black Economic Empowerment Act No. 25899, 2004). Formal property rights are also under pressure in South Africa (Minister of Public Works, 2020), suggesting an informal and indeterminable system of access to land is emerging. Suchá et al. (2020), in a study of urban agriculture in Soweto, highlights that informal "perceived" tenure security is as effective, if not more effective, than formal tenure (2020:6) in stimulating investments on land. Farmers build fences in order to enhance tenure security: "Fencing represents physical protection against thefts which can also be considered as a tenure-building strategy, even in cases where farmers do not hold any land rights … and which might encourage farmers to enhance their investment" (2020:4). In a context of fluid property rights, governance will thus be affected by this ability of actors to "infrastructure" (Gebreyes, 2018; Nogueira et al., 2020) arrangements or "produce urban agriculture" (Siegner et al., 2020) through their actions.

"Infrastructuring" allows actors, including academics, to "produce" systems to their advantage. Siegner et al. (2020) note the "multifunctional" benefits of urban agriculture that creates incentives to "produce" it in different ways. Siegner et al. (2020: 567) contrast the "social and ecological benefits" of urban agriculture with the "productivist" way commercial agriculture is measured. Urban agriculture produce (and thus "infrastructures") social and ecological effects that may be more important than mere food production.

A situation where urban agriculture's potential is not met, would likely lead to "infrastructuring" activities to promote the policy and public support available for urban agriculture. To govern the nexus for sustainability, a new set of opportunities have to be "infrastructured" so actors can "produce" specific benefits like health or sustainability in the way they take action on food, water, land, energy, and waste. This emergent theory of social change, which has implications for the formal regulation of society, indicates actors, and stakeholders will exploit opportunities for engagement and change. A public innovation lab is suggestive of a new paradigm for governance, closely based-on engagement opportunities and methodologies, that can align self-interest with the interests of others. This intersubjective contest can govern for "sustainability."

GOVERNANCE FOR SUSTAINABILITY

Sustainability as "meeting the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987) is conducive to a self-regulating system that meets human needs through the protection of nature. This implies "deliberate self-regulation, from personal action to geoengineering schemes" (Lenton and Latour, 2018: 1,067), including "large scale mobilisation of scientists, activists, and citizens" to link the agency of nature with social and economic systems, so it can continuously provide food, fibre, fuel, minerals, and all other resources for humans. "The challenge is to support diverse autocatalytic networks of human agents that can propel transformations towards goals such as sustainable energy, fuelling the efficient recycling of resources" (Lenton and Latour, 2018: 1,067). Sustainability will emerge if these networks can "infrastructure" actors and stakeholders, society, and enterprises to create a self-reproducing system based-on ecological limits.

Governance for sustainability ought to ensure ecosystem functioning for human life, and this implies the following (Lenton and Latour, 2018: 1,067):

- Recycling and feedback loops and distributed control in industry and circular business models that enable "autocatalytic" networks to engage directly with the governance and transformation of such processes;
- Long-term structures that operationalise the above, including the establishment of "sensors" to release information on planetary processes and limitations; and,
- Networks and relationships need to be built amongst humans, to create the requisite density amongst people for autocatalytic communities to emerge.

In the food system, "organic" or "local" food may be consistent with the creation of a sustainable food system. This framing must be consistent from the food as produce and product, downstream to production methods and wastes, and upstream to consumers and distribution and retail systems. This value chain, or peculiar network of scientists, farmers, citizens etc. has to be coordinated to consistently "produce" sustainability at the system, enterprise, or product levels.

Sensors would have to be "animated" to give the network purpose and direction. Social capital would have to "glue" it together. Spaces and places need to be found for people to organise, deliberate and plan. Media, technologies, and activities need to operationalise these plans. Malan (2020c: 34) describes how Slow Food's slogan of "Good, Clean and Fair" has animated a whole set—or "cascade"—of activities, from farmers' markets to public conferences, and this is consistent with the seed example above. This network that "created" it, may have been transient, but echoes Jensen and Orfila's (2021: 565) description of a symbiotic community in the food system. This community aims at:

> Creating a symbiosis between communities officially classified as multiply deprived, underutilised local assets and infrastructure, and the activities of those operating within the local food sector that are potential sources of critical resources [and this] presents opportunities for myriad beneficial food production, processing, distribution and education hubs.

Recent discussions of the governance of the South African food system towards sustainability and/or food security is consistent with how an autocatalytic network or symbiotic community realises sustainability. The South African food system produces "alarmingly high levels of food waste"; "is a major source of greenhouse gas emissions"; and "depends on several other systems" to function (Battersby et al., 2015: 47; 48). The "broader food system sustainability challenges intersect with a number of structural food system challenges" (Battersby et al., 2015: 48). In this regard, practises such as maintenance of agro-ecology (Siegner et al., 2020), food sovereignty (McMichael, 2014), and organic production (Battersby et al., 2015: 52; Csortan et al., 2020), have been suggested as a frame to guide action, and these choices will influence how the community, network or political activity will be structured and animated.

Siegner et al. (2020: 581; see also Jensen and Orfila, 2021: 564) equates agroecology with "synergistic social, cultural and ecological dimensions." This has consistency with an approach that understands how people "navigate" (Battersby, 2012: 155) their own foodscapes and their "households' actual food geographies" (Joubert et al., 2018: 147). This suggests governance for sustainability needs to frame the governance of the nexus as amenable to change by actors' own volition.

GOVERNANCE AND SUSTAINABILITY: ANIMATION, POLYCENTRIC GOVERNANCE, AND FACILITATION

"Governance" as the creation and enforcement of rules and regulations is often accompanied by a vision of an ideal end state, and this creates narratives that frame an issue in a particular way. The idea of "food security," defined as the availability, accessibility and acceptability (a.o.) of food at "all times" leads to a welfarist or "assistencialist" conception of governance (Clayes, 2015; Haysom, 2015). This allocates power to specific actors like relief agencies and reproduces hierarchical systems. Sustainability however demands that we transform them.

A public innovation lab allows alternative frames or narratives to emerge. The idea that actors should "draw on resources" (Malan, 2020c) in a lab and combine them (Malan, 2020b) in their own projects' frames action differently than a welfare frame. This identifies the autonomous actions of entrepreneurs—or local actors—as key to change. Framing sustainability as amenable to local action by autocatalytic networks, moves beyond "open and transparent engagement" (Pereira, 2014: 39; Battersby et al., 2015: 63) and mere "mechanisms for stakeholder involvement" (Roosendaal et al., 2020: 25). We must enable actors to practise a form of "bricolage" in building up such narratives and networks so they can link diverse issues (Sidibé et al., 2018: 96). To operationalise environmental issues, and address the structural constraints underpinning them, such a lab would need to integrate multiple cross-cutting perspectives holistically (Candel, 2018: 105). This enables a polycentric governance that integrates multiple perspectives (Termeer et al., 2018: 86) that would create a social division of labour appropriate for the issue at hand. This flexibility would be hard to achieve without deep engagement with people.

To allow governance to adapt and address new or novel issues and changes (Roosendaal et al., 2020: 110; Termeer et al., 2018: 86) it needs to "improvise" groups in society that cross-cut current divisions, so that they can produce "symbiotic" enterprises, nested in activist, educational, and other communities. These can create economic and social benefits based-on the conservation and productivity of the environment.

Pereira and Drimie (2016: 27, 29) bring this to bear on the construction of "a strong durable global food movement" and "…institutions that can convene and facilitate multisectoral action." Transitions would need existing actors to coordinate with new opportunities and actors, and they may need a "safe space" (Pereira et al., 2015) like a public innovation lab to do so. It may well be an essential part of governing for sustainability.

Labs' ability to "infrastructure" new means to govern depends upon the design of the methodology of interaction. Regeer et al. (2011: 208) presents workshop methods as tools "for Alliance Building" and "for Co-creation" and "for Embedding and Alignment" as part of a "connected values" approach. Pereira (2021: 2), pertinently, advocates for a hybrid of the "Mα̃noa" method and the "Three Horizons" framework which helps in "considering the possible pathways and points of intervention that link the present to our future visions." Methods have clear networked and systemic and governance effects through the way they create communities amongst peers that would further a progressive agenda.

Digital governance utilises social media as facilitatory means, and below we describe some of these. "Inscription devices" (Williamson, 2015: 259) enable the digital creation of networks: "Through the hashtag, the histories and methods of various different organisations and actors … are hooked up, interwoven with one another, and stabilised as a coherent body of knowledge and practises." An "inscription device," in stabilising reality, indicates how to commence with the creation of an autocatalytic network. Social media offers opportunities for "self-regulation …distinct from the corporate platforms" and this is one of "the great democratic possibilities of the social media age" (Flew, 2020: 2). The hashtag suggests broad solidarity and mobilisation opportunities is possible through a "platforming intersectionality" (Christian et al., 2020: 1) which could create "entrepreneurial solidarities" (Soriano and Cabañes, 2020). The "ability to affect and be affected" (Carlson and Frazer, 2020: 2) through peer-to-peer networks and movements is an instance of intersubjective governance.

SOURCES OF KNOWLEDGE FOR THIS CASE STUDY

This reflective essay is based on a long-term open-ended research programme, based-on participant observation and reflection, by an activist-academic, of the change processes that occur in the food system. The author organises and promotes the Lab not as a neutral actor but as a committed activist-academic. The author's leadership position in the project is illustrative of a "transformative capacity" and "advanced forms of leadership, resources, and skills; target agenda setting, policy planning, implementation and enforcement, and long-term embodiment" (Termeer et al., 2018: 87). The content the author creates includes the development of an editorial and report on each event, the development of an unpublished manuscript, a fieldwork diary, additional writings as they appear in third-party publications (including websites) and the information available on the iZindaba Zokudla Facebook page (https://www.facebook.com/IZindabaZokudla) and the website iZindabazokudla.com.

This article draws on the information mentioned above, supplemented by observations inside, and outside the lab, including stakeholders and how they approach the author in order to gain access to the farmers and entrepreneurs who frequent the Labs. The Labs attract between 100 and 400 participants per event, and this indicates the popularity and need for such an intermediary institution between actors and stakeholders. The Labs' Agenda and the important "announcement hour" have mobilised NGOs, Academics and researchers, local and other businesses, journalists, and others and they actively uses the Labs to further their own ends, albeit in a public arena. Actors have made available opportunities in these labs, and these include offers and requests for land, for training, for new technology and new business opportunities. Recording and diarising these events enables the author to comment on a wide range of issues relevant to food systems change, and in this article these insights are generalised to governance and the idea that we could govern through a public innovation lab.

The descriptions in this article derive from public activities and some persons may be identifiable through these. However, descriptions are abstracted to protect their identity, and also to focus the discussion on key theoretical issues and not on persons and circumstances. This approach has been approved through an institutional review by the author's host institution (Humanities ethical clearance no. REC-01-131-2020). The tone of this essay is therefore abstract, reflective and argumentative, in order to reflect, and allow others to reflect, on governance.

IZINDABA ZOKUDLA AS MEANS TO GOVERN THE NEXUS

Three key themes cross-cut all the governance issues identified above. After I present the case study background below, I move to reflect on how facilitation in the Farmers' Lab proceeds, and this includes reflection on both the open-access events, and the digital or virtual means that are available. I then focus on how people participate in the Farmers Lab, the website, and Facebook. This enables a lab to reflect on society and is described in order to conclude the essay. This thick description allows us to comment on how progressive governance of the nexus can proceed.

BACKGROUND: WHAT IS IZINDABA ZOKUDLA?

iZindaba Zokudla's Farmers Lab is held mostly once a month on the Soweto Campus of the University of Johannesburg. The Virtual Lab is a webinar-type programme that presents panel discussions on key topics in the food system—some relevant to the Facebook Groups on the Facebook Page. The project is developing outreach programmes in the School of Management at the University of Johannesburg for future implementation.

The Farmers' Lab exemplifies the character of iZindaba Zokudla and was created to collapse action research methodology into an event. Action research depends upon small-group interaction (Burns, 2012: 98). However, agriculture is mainly a market-based activity, with change occurring outside in the market context. This allows synergies to emerge in society made by individual entrepreneurs. Hence, it is necessary to implement methods not amongst small groups, but amongst individuals in society.

The Farmers' Lab is a "festival" type of event implemented in a food system that laboured under many centuries of colonialism and apartheid and is permeated by large agricultural producers with certain hegemony over the food system (Cochet et al., 2015) that would maintain their position in the food system at the expense of innovation (Van der Ploeg, 2016) and are likely to exploit emerging producers. Small urban producers are located in "townships" where there is a dearth of entrepreneurial activity (Mahajan, 2014) but significant attempts to build a new society. The Farmers' Lab—open to these influences—is an "assembly" and not a well-defined "association" or "organisation." This open bordered assembly underscores the need to make deliberate methodological choices in how engagement will take place.

The genesis of the Lab stems from "workshops" that were conducted with stakeholders locally and globally (11 March 2014) through a webinar, in order to first establish a farmers' market. Four attempts ended in failure, but this motivated others to create the Soweto Market Place (https://www.facebook.com/thesowetomarketplace/). After this, the Farmers' Lab was created, and the pressure the author experienced from diverse entities outside the University to realise this, suggests such a lab has effects in the "infrastructuring" activities of actors.

The referral system established at the UJ that links to appropriate entities in the University, suggests a form of polycentric governance is necessary for effective governance of the nexus. Such an ecosystem is facilitated by organising the Lab not as a membership association, but as an open assembly of persons. This invites actors to freely engage with others, and this freedom to create associations can achieve progressive effects through dedicated facilitation methodologies.

FACILITATION

iZindaba Zokudla affords emergent entrepreneurs' access to two main fora, the Farmers' Lab and the Virtual Lab. The Virtual Lab aims to organise emergent producers into communities of practise (Wenger, 1998). This form of group organising conceptualises control over the group as stemming from inside the group. Groups can develop their identity through own materials and profiles and "mini-documentaries" on the website, which forms the basis for future collaboration in outreach programmes. Actors will be able to develop a "reputation" alongside their identity profiles which will enable actors to self-select whom they want to work with. This leads to less hierarchical group characteristics that is important for the autonomy of entrepreneurs.

A community of practise aims at the maintenance of the group, so the group can mediate economic entry—establishing an enterprise or trading—amongst themselves. To protect such a group from enrolment into vested interests, we need to afford actors in these groups multiple paths of development, so they can by-pass hegemonic interests. Malan and van der Walt (2019: 15–16) set out how this may take place.

- Group formation has to take place in a plural context blending real-life sessions and digital activities. Themes or narratives create groups identities, and specific aims, like a "local" food system;
- Groups need to self-realise themselves through knowledge, communication and solidarity, and this will enable them to develop their interests. A flexible ecosystem enables people to make their own decisions on production supported by the opportunities available in society;
- A plural context fostered by alternative knowledges and practises enables innovation and is necessary to guard against exploitation and domination. Sustainable production models, like circular enterprises, offers clear advantages over current production methods. When alternatives are offered to farmers, new patterns emerge in society;
- A community of practise is a value chain, and this approximates an autocatalytic network or symbiotic community and has potential as a steering mechanism of economic growth. Value chains can now be controlled and steered amongst peers, and alternative and experimental systems of production can be set-up or imagined inside the safety of a group; and,
- The above will create a new ecosystem that approximates a sustainable food system by allowing groups to re-define an economic sector or activity, albeit at the local scale.

The above will enable emergent actors to create and control the networks within which they act. This creates a broad context wherein people can participate. To realise such a system of innovation we need to design the opportunities which structure how actors participate in iZindaba Zokudla's Labs.

PARTICIPATION

The open access organising that takes place in the Farmers' Lab on the University of Johannesburg Soweto Campus, and the digital means afforded to them, structures actors' activities as it controls the proceedings in the Labs. These activities create narratives to structure action, develop methodologies of engagement, and this allows entrepreneurs to form their own networks.

The Lab and Its Agenda

The Lab is structured in ways that were developed by trial and error but is designed so that anyone can participate and influence the proceedings on the day. To do so, the following features are highlighted:

- The Lab, to create a sense of belonging, opens with a song, a poem or a prayer, as is common practise amongst local community-based organisations;
- The Lab is advertised through a Short Message System on mobile phones that is able to reach those without internet connectivity. This is shared further on several WhatsApp groups by the author and recipients;
- An Editorial developed by the facilitator sets the tone in each event and enables control over proceedings through narratives that frame key issues in particular ways to enable strategic issues to be identified and deliberated upon;
- An announcement hour which allows anyone to take the stage and pitch or advertise their enterprise or products or activism. This takes up the bulk of the day. Actors use this opportunity to find new clients and markets, and to create groups amongst themselves. These pitching sessions are immediately photographed and posted, and are retrievable on Facebook;
- The theme of the day is often dealt with by inviting scientific and local experts to give a lecture on a given topic. This has ranged from Mycotoxins in the food chain, to pollution in soils, to organic or permaculture production, catering, and to organise additional events (like the Slow Food Soweto Eat-Ins). Local experts juxtaposed next to scientific experts makes knowledge accessible (often in the vernacular) for activism or enterprise development; and,
- The yearly schedule for the Lab was in the past developed through an end or beginning of the year participatory planning session. Speakers proved impossible to secure, but the announcement hour themes are often suggested for future events. This indicates the Lab can respond flexibly to new and pressing concerns as they emerge.

The above structure can be adapted to any open participatory event to allow the implementation of pertinent participatory methodologies, and in turn, to focus on a particular issue as it appears in the nexus. If a lab allows some to act, led by a sustainability narrative and within a pluralism that off-sets powerful interests, we need to understand how this allows actors to form their own networks and how these can promote sustainability.

NETWORKS

Asynchronous social media leaves a digital record of proceedings that is valuable for independent organising. Social media and its viral character, in the form of WhatsApp groups, groups on Facebook, groups on aparate.co, and groups and "members" on the iZindabazokudla.com website allow independent organising by actors themselves. The author exemplifies this, and has started developing training materials on another platform, the Start Up Tribe (https://www.thestartuptribe.org/courses/start-a-farm). Companion pages have emerged that run alongside iZindaba Zokudla (see: https://iZindabazokudla.wordpress.com/; https://www.facebook.com/IZindabaZokudlaPage). This creates a pluralism, and this promotes people's own autonomy outside the Lab. This allows them to construct enterprises with multiple solidarities inside, and outside the Lab.

iZindaba Zokudla avoids using "inscription devices" in a hegemonic way. It keeps no records or "data" on participants except anonymous phone numbers (although the Facebook page and Website are open to analytics). Powerful actors have to use these open systems to recruit and mobilise entrepreneurs, offsetting their hegemony. The Lab has seen retailers commit—in public—to specific prices for farmers (Malan, 2020c: 35), and several farmers are trading with this retailer. Participants in the lab has also exposed fraudsters who might want to exploit farmers for their own gain. A broad open ecosystem of interaction alongside such a Lab shows such progressive governance effects.

Communities are created so they can manage their own presence on social media and to choose their own groups and avenues for empowerment. This safe space stems from the "neutral" role of the university but also the subjective interaction amongst actors and stakeholders, which creates a contest amongst differing voices. This suggests a programme of stakeholder engagement, populated with information, opportunities, events, media, and technology, could affect how society will react and deliberate on the key challenges in sustainable governance.

REFLECTION

A public innovation lab creates opportunities in society to reflect and critically engage with governance. Reflection needs to be designed and operationalised, and social media affords us explicit opportunities in this regard. However, additional reflective opportunities are created by the narratives and frames that can be brought to such a lab, by the activities of leaders in such a context, and by effects a lab would have on actions taken in society. Actors use the material from such a lab to "infrastructure" their enterprises and also their immediate contexts to promote their interests and this is the driving force of sustainability. Sustainability needs to be framed as an explicit objective, and technical and other considerations subsumed under this narrative.

iZindaba Zokudla holds no official power, but its activities point to a critical alternative to mainstream agricultural development, that "homogenises" (often through "Master Plans") agriculture, whilst sustainability implies critical engagement with and the transformation of vested interests. iZindaba Zokudla's independence and its connexions to actors on the ground allows the creation of alternative means for agricultural development that can be institutionalised as an alternative to extension programmes. This will enable us to operationalise sustainability either through engagement, trial and error, or through the actions of others.

CONCLUSION: GOVERNING THE SUBJECT FOR SUSTAINABILITY

iZindaba Zokudla aims at progressive outcomes, and this serendipity of progressive outcomes may be due to its ability to infrastructure society or recreate the social contract. A public innovation lab that pluralises the governance of the nexus allows networks to complete the labour needed to realise sustainability. A Lab as a process of engagement develops narratives that coordinates action amongst many and allows dedicated networks or communities to take action. A public innovation lab creates these opportunities and is suggestive of a new approach to social change that operationalises the volition of concerned and active groups in society, and makes them the drivers of sustainability.

DATA AVAILABILITY STATEMENT

The datasets presented in this article are not readily available because the data has been be abstracted and anonymized to protect identities. Requests to access the datasets should be directed to nmalan@uj.ac.za.

ETHICS STATEMENT

Written informed consent was not obtained from the individual(s), nor the minor(s)' legal guardian/next of kin, for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

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

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Does Information Acquisition Influence the Adoption of Sustainable Land Management Practices? Evidence From Mpumalanga Province South Africa

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Agricultural information plays a vital role in adopting agricultural technology. The study explored if information acquisition is related to the adoption of sustainable land management practices (SLMP) and jointly decided in Mpumalanga Province of South Africa. Primary data were collected through face-to-face interviews, using a proportionate random sampling technique to get 250 smallholder farmers to participate in the survey. A seemingly unrelated bivariate probit (SUBP) model and a recursive bivariate probit (RBP) model were adopted to examine the objective. The statistical estimation of the SUBP showed that there is a relationship, an empirical association between information acquisition and SLMP; while RBP estimation showed that information acquisition was exogenous in the adoption model; thus, the decision to acquire information and adopt SLMP was not jointly decided. Therefore, the study presents the determinants of information acquisition alongside with the adoption of SLPM. The result from the SUBP model, indicated that the years spent in school; agricultural extension service; the number of extension visits and the years of farming, influenced both information acquisition and the adoption of SLMP. The cost attached positively influenced the adoption of SLMP; while gender, marital status and age only influenced the information acquisition.

Keywords: information acquisition, adoption of SLMP, SUBP, RBP, South Africa

BACKGROUND

Smallholder farming continues to play a significant role in South African agriculture (Pienaar and Traub, 2015). However, climate change, poor infrastructure, soil degradation and tough economic conditions amongst others are the major constraints facing small-scale agricultural productivity in sub-Saharan Africa (Kom et al., 2020). Land degradation and climate change are the double threat which has a huge impact on human security, food security, loss of biodiversity and ecosystem services, land availability for agricultural production (Behrend, 2016; Davies, 2016). In South Africa, land degradation and especially soil erosion is currently a major concern both in commercial farming and smallholders farming sector (Critchley and Netshikovhela, 1998; Oduniyi, 2018). The degradation of agricultural soils negatively impacts soil health and productive capacity.

Consequently, Food and agriculture organization (FAO, 2009) reported that about a third of the world's soil has already been degraded as a result of land degradation, intensive farming, climate change, chemical-heavy farming techniques and deforestation which increases erosion. The author further explained that it takes 1,000 years to generate three centimeters of topsoil. However, should the present rate of degradation persist, it is obvious that virtually the entire world's topsoil could disappear within the space of 60 years (FAO, 2009). Given the findings, it is thus pertinent that an urgent approach and concept be adopted to stem or reverse the calculated disappearance of the topsoil. However, sustainable land management practices (SLMP) could be the way forward to curb this *environmental pandemic* which has become a social issue globally. SLMP are needed to reverse and renew degraded lands, mitigate and adapt to the changing climate.

Sustainable land management practices (SLMP) are schema that deals with the fundamental constituents of the global life support system. As defined by the TerrAfrica partnership (TerrAfrica, 2006), *"SLMP is the adoption of land-use systems that, through appropriate management practices, enables land users to maximize the economic and social benefits from the land while maintaining or enhancing the ecological support functions of the land resources"*. The exploitative occurrence of the negative effects of natural resources experienced by food producers is so ubiquitous that it has given rise to a universal and growing awareness that productive lands are scarce, thus; divulging the knowledge that the land under cultivation needs greater intensive care. Moreover, it cannot be gainsaid that sustainable land management is the sub-structure for grounding sustainable agriculture in addition to functioning as an integral strategic element that enables a perennial sustainable development, besides serving as a tool of poverty alleviation

Additionally, SLMP focus on alleviating the detrimental impact of climate change on productivity, concurrently preventing the degradation of natural resources with issues relating to ecological, economic and socio-cultural dimension (Olsson et al., 2019). Intrinsically, the primary aim of SLMP is to incorporate people's coexistence with nature in the long term so that provisioning, regulating, cultural and supporting services of ecosystems are ensured (The Intergovernmental Panel on Climate Change, IPCC, 2013). It is a key measure in adapting to the effects of climate change. The essence of adopting SLMP is to develop a synergism between environmental issues and food security. In South Africa, the World Overview of Conservation Approaches and Technologies (WOCAT) has instigated for years with numerous approaches and technologies been documented on SLMP. However, several practical problems arise in espousing and fully adopting SLMP owing largely to information gaps on SLMP as well as indifference among farmers toward transitioning from traditional to modern farming practices (Olawuyi and Mushunje, 2020).

Agricultural information plays a vital role in adopting agricultural technology (Rivera, 2000; Bonabana-Wabbi, 2002; Jabbar et al., 2003). Agricultural information is a long-term stimulus for agricultural development and also an important indicator of agricultural modernization (Zhang et al., 2016). Perhaps information acquisition is a prerequisite for the introduction of new agricultural technology such as SLMP. According to Mwangi and Kariuki (2015), access to information creates awareness and influences farmers' decisions to adopt new agricultural technology. However, having access to information does not guarantee adoption of SLMP due to heterogeneity composition which makes farmers perceive and assess information differently leading to adoption and dis-adoption of new technology such as SLMP (Uaiene et al., 2009). In the same vein, this information is acquired through agricultural extension officers, farmers' groups, etc. (Vidanapathirana, 2019). Information acquisition in the study area is shared within the social group such as the farmers' group.

However, the bone of contention in this regard is to know whether information acquisition and the adoption of SLMP are related and jointly decided. Although there has been some literature on SLMP such as the impact of adoption of SLMP on welfare, adoption and determinants of SLMP, but nothing has ever been written on the effect of information on SLMP adoption in South Africa. Thus, this study serves as a blueprint and sets the pace for future research work. The outcome will help the farmers, government, policy-makers and the stakeholders concerned to understand the linkage between information acquisition and the adoption of SLMP; and if the decision to acquire information and adoption of SLMP is jointly determined and decided. Overall, this will provide insight into the factors that influence the information acquisition and adoption of SLMP in the study area. It is, therefore, worthwhile to conduct this research.

Research question: Does information acquisition and the adoption of SLMP related (simultaneously determined) and jointly decided.

Hypothesis: The hypothesis for this study is stated in the null form: Adoption of sustainable land management and information acquisition are not related (not simultaneously determined); there is no significant relationship between the two and are not jointly decided.

MATERIALS AND METHODS

The Study Area

The study was conducted in the Gert Sibande District Municipality in Mpumalanga, South Africa as shown in **Figure 1**. The district covers an area of 31,841 km², which makes it the largest district in the province. The district is divided into seven local municipalities, namely: Govan Mbeki, Chief Albert Luthuli, Msukaligwa, Dipaleseng, Mkhondo, Lekwa, and Dr. Pixley ka Isaka Seme. To the north, it is bordered by the Ehlanzeni and Nkangala District Municipalities, to the south by KwaZulu-Natal and the Free State, to the east by Swaziland and to the west by Gauteng. The major economic sectors are mining, agriculture, energy and manufacturing. The municipality is chosen because of its high concentration of subsistence farmers, and similarly, SLMP has been mapped out and adopted into this province long before now.

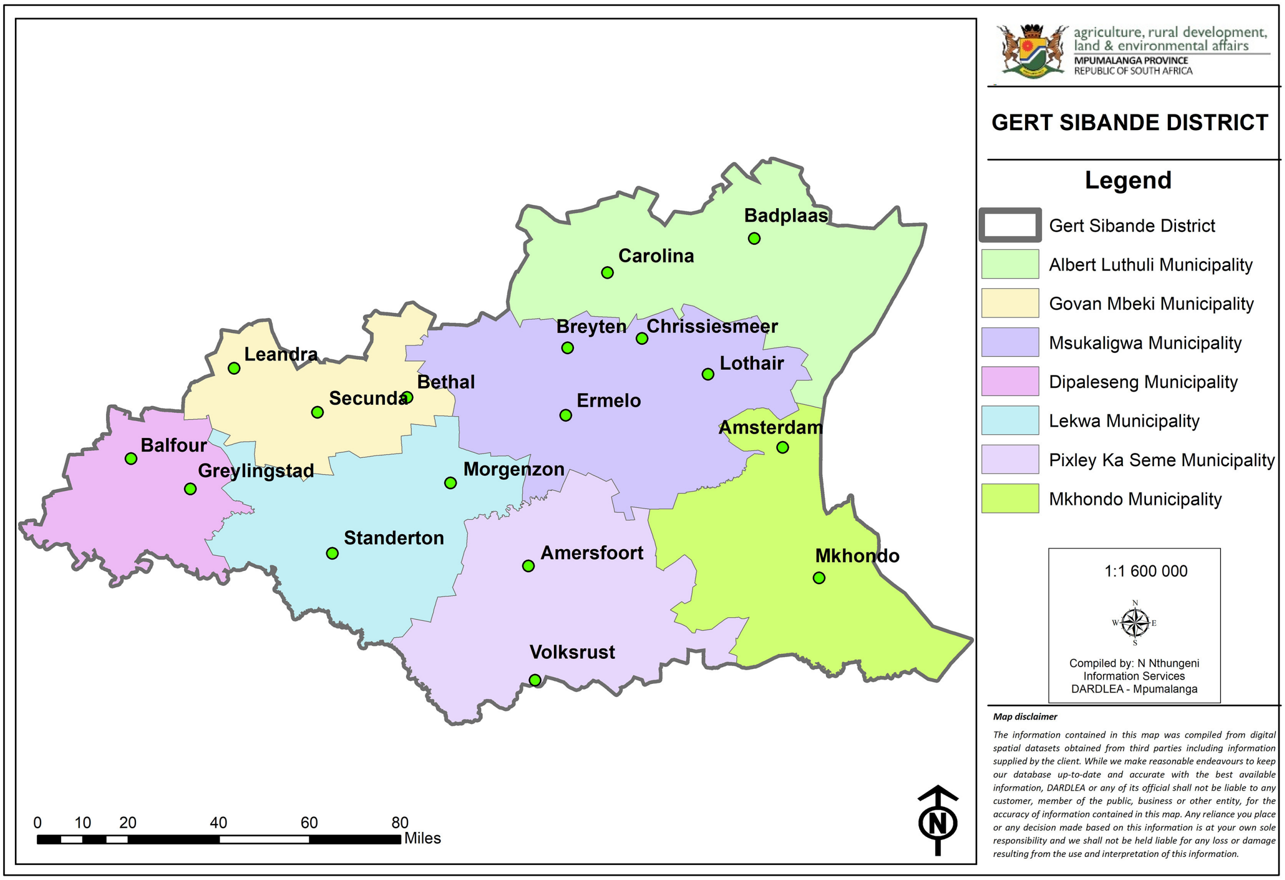

FIGURE 1 | Map of Gert Sibande District.

Sampling Technique and Data Collection

Cross-sectional data were used for this study. Data was collected between December 2019 and August 2020, using a semi-structured survey questionnaire validated by two agricultural economist experts (independent experts). A reliability test was performed on the questionnaire to ascertain its use. The questionnaire contained logic flow questions aimed at farmers' demography, information acquisition of SLMP, social groups and the adoption of SLMP. The survey was conducted through face-to-face interviews; each session with the farmers lasted 40 min. A representative sample size was determined, using Slovin's formula given in Equation (1) after which a total number of 250 questionnaires were administered to the maize farmers in the district by four trained enumerators who translated the questionnaire into local language for farmers to understand. A proportionate random sampling technique was used to select the sample size where each local municipality represent a stratum from which sample were randomly obtained. This was achieved by adopting a quantitative model, as presented below:

$$n = \frac{N}{1 + N(e)^2} \tag{1}$$

Where n is the sample size,

N = total population of maize farmers in the seven local municipalities across the district

e = maximum variability or margin of error (MoE). This is estimated at 5% (0.05)

1 = probability of the event occurring

250 = the number of respondents sampled or sample size.

Table 1 shows the distribution of sample size collected according to each municipality or stratum.

TABLE 1 | Sample size taken in each municipality (stratum).

Municipalities	Frequency	Percent
Govan Mbeki	42	16.8
Albert Luthuli	33	13.2
Mkhondo	60	24.0
Msukaligwa	34	13.6
Lekwa	32	12.8
Pixley Ka Seme	19	7.6
Dipaleseng	30	12.0
Total	250	100.0

Source: Author's computation (2021).

Data Analytical Techniques

Data were analyzed, using both descriptive and inferential statistics. Descriptive statistics such as mean values, standard deviation and percentages were used to describe the farmers' socioeconomics, information acquisition and adoption of SLMP. Subsequently, a seemingly unrelated bivariate regression (SUBP) and recursive bivariate probit (RBP) model were used as inferential statistics to investigate if the decisions to acquire information on SLMP are jointly determined and simultaneously lead to the smallholder maize farmers adopting SLMP.

Conceptual Framework

In reality, the decision of a farmer to adopt sustainable land management practices preceded by information received or acquired on SLMP. This information is mostly shared and acquired by the social capital group. Thus, every member of a social group (mostly farmer groups) decides whether or not to make use of the information. Thus, there occur unobserved characteristics leading into endogeneity problem, in which failure to take account of it will lead into biased and spurious result (Owusu et al., 2020; Oduniyi and Chagwiza, 2021). However, if the net benefit associated with the adoption is positive or greater than otherwise, then the farmer decides to adopt the innovation. In this instance two procedures occur that are dichotomous and mutually decided or simultaneous to each other. This requires joint estimation of the two sets of procedures or equations relating to decision models which do not necessarily involve the same independent variables or regressors but contain the same error terms just like in the instance of seemingly unrelated regression equations (SURE) model. However, the dependent variables involved are the binary options; information acquisition on SLMP can be represented as ($y_1 = 1$) or otherwise ($y_1 = 0$). Correspondingly, for adopting or non-adopting SLMP can be represented by ($y_2 = 1$) or ($y_2 = 0$), respectively.

Model Specification

Seemingly Unrelated Bivariate Regression

In other words, a seemingly unrelated bivariate regression (SUBP) was employed to determine if information acquisition relate to the adoption of SLMP; or if the information acquisition on SLMP simultaneously determined alongside with the adoption of SLMP. Following Thuo et al. (2014), Tuna et al. (2017), and Olawuyi and Mushunje (2020), SUBP was used to determine a joint relation of two binary equation models. This model is often used to investigate if two dependent variables mentioned are correlated with unobserved characteristics among farmers. To some extent the model is similar or comparable to bivariate probit; and it generalizes the index function model from one latent variable to two latent variables that may be correlated (Seyoum, 2017). This can be mathematically written as follows:

$$y^*_1 = \beta X' + \varepsilon_1 \quad (2)$$

$$y^*_2 = \delta Z' + \varepsilon_2 \quad (3)$$

where: $y_1 = 1$, if $y^*_1 > 0$, otherwise $y_1 = 0$

$y_2 = 1$, if $y^*_2 > 0$, otherwise $y_2 = 0$

y^*_1 and y^*_2 are unobserved latent variables that represent the tendency for awareness

and the decision to adopt SLMP, respectively

The variables y_1 and y_2 denote the observable responses (0 or 1)

X and Z are vectors of covariates

b and d are vectors of unknown parameters to be estimated

ε_1 and ε_2 are joint normal with means zero, variances one and correlation ρ.

As pointed out by Cameron and Trivedi (2009), the coefficient ρ, captures the possible effect of unobserved characteristics on the two equations which could be positive, negative, or null. The error terms are assumed to be zero-mean bivariate normally distributed with unit variance and correlation coefficient (Tuna et al., 2017). The correlation between the errors in the two equations, can be interpreted as the interdependence of the unobserved components in the information acquisition and adoption of SLMP.

Recursive Bivariate Probit (RBP) Model

As mentioned earlier, due to the possible endogeneity, a recursive bivariate probit (RBP) modeling technique was employed to deal with the observed and unobserved selection bias. This technique has also been applied in previous studies (Vall Castello, 2012; Ma et al., 2018). For example, Ma et al. (2018) adopted the RBP model to investigate the impact of cooperative membership on the adoption of organic soil amendments and chemical fertilizer in China. Similarly, in this study, the recursive bivariate probit (RBP) model was employed to establish if the information acquisition of SLMP is endogenous in the adoption of the SLMP model. That is if information acquisition, as an explanatory variable used in the adoption of the SLMP model, is jointly decided with the unobservable factors captured by the error term (Thuo et al., 2014). Thus, the presence of endogeneity advocates that both choices made from the two equations are jointly decided. The model can be represented, as shown below:

$$y^*_1 = \beta X' + \varepsilon_1 \quad (4)$$

$$y^*_2 = \alpha y^*_1 + \delta Z' + \varepsilon_2 \quad (5)$$

It should be noted here that the parameters expressed are the same as in the SUBP above; however, αy^*_1 denote the inclusion of dependent variable (awareness of SLMP) in the first and second equation.

Table 2 shows the variables used in the model and their measurement.

RESULTS AND DISCUSSION

Descriptive Analysis Results

With **Table 3** presents descriptive statistics of the sample of the explanatory variables used. The average age of the smallholder maize farmers in the study area was found to be 48 years, with an average of 10 years spent in school. The mean visit by an extension officer was found to be at least twice a month. The majority of farmers had an average of 11 years of farming experience and the mean farm size was found to be 123

TABLE 2 | Variables used in the model and their measurements.

Variables	Description and variable measurement	Expected sign
Adoption of SLMP	Dummy, 1 if yes, 0 if otherwise	
Information acquisition	Dummy, 1 if yes, 0 if otherwise	
Explanatory variables		
Gender	Dummy, 1 if household head is a male and 0 if otherwise	+
Age	Number of years (Continuous)	–
Years spent in school	Number of years (Continuous)	+
Farm size	Size in hectares (Continuous)	+/–
Years of farming	Number of years (Continuous)	+/–
Access to ext ser	Dummy, 1 if yes, 0 if otherwise	+
The cost attached (R)	Cost in ZAR (Continuous)	+
Marital status	Dummy, 1 if household head is married, 0 otherwise	–
Member in soc org	Dummy, 1 if yes, 0 if otherwise	+
Access to credit	Dummy, 1 if yes, 0 if otherwise	+
Freq. of extension visit	Categorical (1 = Not at all, 2 = Seldom, 3 = Frequently)	+

Source: Author's computation (2021).
+, positive; –, negative.

TABLE 3 | Summary statistics of the variables used.

Variable	Mean	Std. deviation
Gender	0.524	0.500
Age	48.472	12.285
Marital status	0.472	0.500
Years spent in school	10.268	4.842
Extension service	0.816	0.388
Number of extension visits	2.288	0.779
Member of organization	0.684	0.466
Years of farming	10.828	6.774
Farm size	123.016	242.980
Cost attached	0.796	0.404
Access to Credit	0.472	0.500
	Percentages (%)	
Adoption of SLMP	Adopters (93.2%)	Non-adopters (6.8%)
Information acquisition	Acquired (70.8%)	Non-acquired (29.2%)

Source: Data analysis (2021).

hectares. Similarly, about 93% adopted at least one practice of sustainable land management while 71% claimed that they acquired information on SLMP.

Empirical Results

The study examined the linkage of how information acquired by farmers on SLMP relates to adoption. The two models used explore variables considered to be exogenous to the two dependent variables. The exception is information acquisition in the RBP models, a matter that is subjected to econometric testing. From the SUBP result, the first procedure was to use Wald test (LR test) to evaluate the null hypothesis that rho is zero (0). The value of rho (5.90e-10) was significant at the 1% level (Chi-square = 35.1773, df = 1, p-value = 0.0000). The result indicated the probability that a farmer acquired information was indeed related to the probability of adopting SLMP through unobserved effects captured in the error terms of the models. The positive sign for rho in the SUBP model indicates that the two variables are complementary to each other. A way to think about these results is that information acquisition and the adoption of SLMP worked together as a strategy for improved productivity. Thus, there is a relationship between the information acquisition and adoption of SLMP. This finding is consistent with the submission of Huth and Allee (2002) and Moreno and Sunding (2003) who acknowledged that positive value for rho suggests a complementary decision variable.

In the RBP model, as shown in **Table 4**, the non-statistically significant (0.1160) results of the Wald test (LR test) for rho = 0 indicated that information acquisition is exogenous which suggested that the decision to acquire information and adopt of SLMP was not jointly decided. This is not surprising as some farmers who adopted SLMP did not acquire information, vice versa. The reason is not farfetched from the fact that most smallholder farmers practice sustainable agriculture unaware. They still practice primitive form of agriculture such as bush fallow, mulching, planting cover crops, crop rotation etc.; which are typical examples of SLMP, thus, they adopted SLMP unknowingly without acquiring information on SLMP. Hence, information acquisition and adoption of SLMP was not jointly decided.

SUBP Model Result for Information Acquisition

The results from the SUBP model revealed that the number of years spent in school (education); access to agricultural extension service; number of agricultural extension visits and the number of years of farming jointly influenced information acquisition and adoption of SLMP. *The years of farming or farming experience* of a farmer was found statistically significant. The result shows that the lower the years of experience, the lower or less likely a farmer acquire information and/or adoption of SLMP, vice versa. This was in support to a report by Alam (2015) who reported that farmers with more experience in agriculture are more likely to adopt agricultural innovation.

The number of years spent in school signifies the education of the head of the household. The result in **Table 5** shows that education was found to be statistically significant and it positively influenced information acquisition and adoption of SLMP. This advocates that an educated or literate household head farmer has a propensity to acquire more information and adopt SLMP. This is confirmed by the findings of LaFerrara (2002) and Haddad and Maluccio (2003) who reported that higher education encourages farmers to seek and acquire more information. This was contrary to Thuo et al. (2014) who affirmed that farmers with more years of education are less likely to adopt new agricultural practices.

TABLE 4 | Recursive bivariate probit.

	Information acquisition		Adoption		
Variables	**Coeff**	**Z**	**Coeff**	**Z**	**dy/dx**
Information acquisition	–	–	2.107	1.18	0.030
Gender	0.445	2.10**	−0.307	−0.88	0.099
Marital status	−0.533	−2.43**	–	–	−0.123
Age	0.031	2.93***	0.025	0.98	0.008
Years spent in school	0.108	4.41***	0.192	2.14**	0.028
Extension service	−1.032	−2.51***	−2.620	−2.74***	−0.276
Number of extension visits	1.089	5.18***	1.441	2.99***	0.273
Member of organization	−0.336	−1.31	0.931	1.84**	−0.065
Years of farming	−0.037	−2.35**	−0.042	−1.79**	−0.009
Farm size	0.000	0.15	−0.002	−1.51	−8.58e-06
Cost attached	–	–	1.955	2.50***	0.028
Access to Credit	–	–	−3.093	−1.31	−0.010
Constant	−3.093	−2.02	−1.924	−2.02	
/athrho	13.821	0.02			
Rho	1	3.11e-09			

LR test of rho = 0: chi^2 (1) = 2.47027; Prob > chi^2 = 0.1160.
Wald chi^2 (19) = 102.70.
Log likelihood = −125.81726.
Number of obs = 250.
**p < 0.01; **p < 0.05; ***p < 0.1 level, respectively.*
Source: Data analysis (2021).

TABLE 5 | Seemingly unrelated bivariate probit.

	Information acquisition		Adoption		
Variables	**Coeff**	**Z**	**Coeff**	**Z**	**dy/dx**
Gender	0.458	2.09**	−0.248	−0.71	0.100
Marital status	−0.526	−2.40**	–	–	−0.120
Age	0.032	2.97***	0.016	0.80	0.008
Years spent in school	0.109	4.45***	0.127	2.10**	0.027
Extension service	−1.030	−2.49***	−1.850	−3.45***	−0.265
Number of extension visits	1.085	5.14***	1.450	3.18***	0.271
Member of organization	−0.342	−1.31	0.821	1.56	−0.064
Years of farming	−0.037	−2.30**	−0.047	−1.80**	−0.009
Farm size	0.000	0.05	−0.000	−1.02	−6.80e-06
Cost attached	–	–	1.159	2.89***	0.019
Access to Credit	–	–	−0.799	−1.32	−0.013
Constant	−2.864	−4.99	−1.924	−1.94	
/athrho	14.390	0.03			
Rho	1	5.90e-10***			

LR test of rho = 0: chi-sq (=1) = 35.1773; Prob > chi^2 = 0.0000.
Wald chi^2 (19) = 104.31.
Log likelihood = −127.05119.
Number of obs = 250.
**p < 0.01; **p < 0.05; ***p < 0.1 level, respectively.*
Source: Data analysis (2021).

Access to agricultural extension services was found to be statistically significant and it negatively affected information acquisition and adoption of SLMP. The result suggests that farmers with access to agricultural services are less likely to acquire information and adopt SLMP. The possible reason could be that, despite having access to the agricultural extension service, little or few information related to SLMP were shared. However, the farmers claimed to have acquired more related information on SLMP from a social capital group, such as farmer's group and cooperative group. This result goes against the study carried out by Katungi et al. (2008) in Uganda who reported that extension activity in the village is an important determinant of information exchange related to agricultural technologies among rural people.

The number of agricultural extension visits were statistically significant and positively influenced the information acquisition and adoption of SLMP. The result suggests that the more visits a farmer received the more likely he/she acquired more information about SLMP. Most farmers explained that more visits provide an avenue to ask questions on the information which they have acquired from the social capital group on SLMP, which becomes easy to adopt. Normally, a farmer with higher extension activity is more likely to engage in a two-way information exchange compared to those with less frequent extension activity. This result is buttressed by Ntshangase et al. (2018) and Oduniyi (2018), who affirmed that access to extension service is not enough; the intensity of the extension services is critical in determining the level of adoption.

Other factors that influence information acquisition and adoption of SLMP independently are:

The gender of the farmers was found to be positive and statistically significant ($p < 0.05$) in influencing information acquisition. The result explained that male farmers are more likely to acquire information on SLMP. The reason for this could be that male farmers dominate the farming industry and they have better access to agricultural resources such as land, agricultural inputs, including information acquisition. Female heads of households compared to their male counterparts are likely to be disadvantaged in their access to a social capital group that facilitates information flow. This result is confirmed by Katungi et al. (2008) who reported that female heads of households are expected to acquire less information on agricultural technologies and new practices compared to their male counterparts.

The age of the household heads was found to be significant ($p < 0.01$), and it contributes to information acquisition. This suggests that the older the household head, the better the chances of acquiring information on SLMP. This is not surprising as most old farmers are used to soil management practices and cultivation practices, such as mulching and crop rotation, which are an example of SLMP. Thus, it is easier for them to relate and acquire information on SLMP. This is interesting as it negates many findings that reported that old age discourages an individual from acquiring information

(Alesina and La Ferrara, 2002; Godquin and Quisumbing, 2006). It should be noted here, that age and farming experience are synonymous. Thus, this conform to the earlier explanation that a farmer with few farming experiences is less likely to acquire information, while a farmer with more years of experience is more likely to acquire information.

The Marital status of the household head was statistically significant ($p < 0.05$) and negatively influenced information acquisition. This explains that a married household head farmer is less likely to acquire information on SLMP. Of course, a married household head will discuss information with his/her partner before acquiring information; however, in most cases, the influence of the other partner rejects the acquisition.

The cost attached to the adoption of SLMP was statistically significant ($p < 0.01$) and found to be positive; thus, influencing the adoption of SLMP. The study suggests that cost involvement increases the probability of SLMP adoption in the study area. The result is surprising as smallholder farmers are not rich and they are always skeptical to cost attached to farm innovation. It is always believed that smallholder farmers' willingness to pay for technology is far low. Although, some farmers claimed that if costs are involved with the opportunity of improving crop yield, then they would not mind paying for it. This result is conformed to Alemu et al. (2021) who reported that smallholder farmers' willingness to pay for SLMP in the Upper Blue Nile basin in Ethiopia was found to be 76%.

Similarly, a study conducted by Takele and Umer (2020) in Homosha, Ethopia found revealed that the total willingness to pay for SLMP among small-scale farmers was found positive and significant. The study concluded that household's willingness to pay more than 66 percent cost for any SLMP to improve agricultural production by examining their total willingness to pay for SLM. It is expected that if net benefits exceed the cost of adoption, then the farmer decides to adopt the SLMP. However, farmers have always looked at new technologies as a way to reduce costs. All the same, this result was supported by The Organisation for Economic Co-operation Development (OECD) (2001) which explained that to survive, farm production must be cost/price-driven. New technology is therefore needed to increase productivity. Farmers must keep up with improvements in technology to stay in business.

CONCLUSION AND RECOMMENDATION

The study examined if information acquisition and adoption of SLMP is related and jointly decided in which both SUBP and RBP were explored. The result from the RBP model revealed that the Prob > chi^2 was not statistically significant, the result of the Wald test (LR test) of rho = 0 shows that information acquisition is exogenous, there is no problem of endogeneity, suggesting that the decision to acquire information and adopt SLMP was not jointly decided.

Similarly, the result from the SUBP estimate explains that rho was statistically significant and positive, the $Chi^2 = 35.1773$, df = 1, Prob > $chi^2 = 0.000$, which suggested that information acquisition and adoption of SLMP are correlated and complementary to each other. The years spent in school; agricultural extension service; number of extension visits; and years of farming influenced both information acquisition and adoption of SLMP. The cost attached to SLMP positively influenced the adoption of SLMP, while gender, marital status and age only influenced information acquisition.

The study therefore recommends that to promote eco-friendly and sustainable agriculture through SLMP, effective training on SLMP and capacity building be established among the agricultural extension officers and that the number of visitations to farmers be increased. Workshops and training on SLMP should be provided to the farmers, to increase awareness, information and adoption of SLMP. Farmers' social group needs to be fortified. The NGO and stakeholders concerned must help with some resources needed by the farmers to improve the adoption of various SLMP at a time.

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 South Africa. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

ST is the fundholder and while OO works on the manuscript. All authors contributed to the article and approved the submitted version.

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Uptake of Climate Smart Agriculture in Peri-Urban Areas of South Africa's Economic Hub Requires Up-Scaling

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Climate variability and change impact significantly on food security and the livelihoods of smallholder farmers making it necessary for the farmers to prioritize investment in adaptation and mitigation approaches, such as climate smart agriculture, to enhance resilience. Climate smart agriculture approaches have been adopted in many countries around the world to address the adverse impacts of climate change on agricultural production. There is limited information about climate smart agriculture adoption by peri-urban farmers in developing countries. The present study aimed to assess the extent to which agricultural activities by smallholder crop farmers in the City of Tshwane Metropolitan Municipality in Gauteng province of South Africa are climate smart, and to establish the sustainable measures to be put in place to enhance the adoption of climate smart agriculture. The study made use of a mixed method design combining qualitative and quantitative approaches. A combination of simple random and non-probability sampling techniques was employed to select the study locations and identify respondents. A sample of thirty-six farmers were selected for the study. The main findings revealed overwhelming awareness of climate change and the impacts thereof on crop productivity and yields. However, the respondents' level of awareness of climate smart agriculture technologies was generally low. Despite the lack of knowledge of climate smart agriculture practices, the farmers were, to an extent, utilizing adaptation mechanisms acquired from indigenous systems or scientific knowledge. Examples of these practices include mulching, cover cropping, crop rotation and use of crop varieties. The study concludes that much more can be done to scale up the uptake of climate smart agriculture in the Gauteng province. The study recommends formal and informal strategies including one-on-one extension programs to raise the awareness of climate smart agriculture technologies appropriate to the unique conditions of the farmers.

Keywords: climate variability and change, climate smart farming practices, smallholder crop farmers, Gauteng province, food security

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INTRODUCTION

Numerous scientific studies have confirmed that climate variability and change severely affect the environment, food production and food security, causing detrimental socioeconomic and livelihood impacts on smallholder farmers particularly in developing countries (Iizumi and Ramankutty, 2015; Elum et al., 2017). Climate change causes a disruption of traditional agricultural practices and the livelihoods of smallholder communities who practice semi-subsistence farming and earn a living through farming (Mathews et al., 2018).

The term climate variability implies the "variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all spatial and temporal scales beyond that of individual weather events" (IPCC, 2018, p.8). Variability may occur naturally due to processes within the climate system or may result from variations in natural or anthropogenic external forcing. On the other hand, climate change refers to a change in the state of the climate identifiable by changes in the mean or the variability of its properties and that keeps on for decades or longer (IPCC, 2018). Climate change is attributable to natural internal processes or external forces including anthropogenic. According to the UNFCCC (2013), climate change is attributable to human activities that alter the composition of the atmosphere while climate variability is attributable to natural causes.

The realities of climate variability and change call for drastic action by farmers to combat the potential detrimental impacts on food production and food security, the environment, as well as the resilience, sustainability and livelihoods. Potential and sustainable action include adaptation strategies which enable farmers to cope with socioeconomic, environmental and agricultural production challenges, such as implementing climate smart agriculture (CSA) (Barnard et al., 2015).

The concept of CSA emerged a decade ago, motivated by a need to develop solutions for the integrated goals of: (a) increasing agricultural productivity and yields, (b) reducing greenhouse gas (GHG) emissions from the agricultural sector, (c) enhancing resilience, and (d) increasing adaptation of farmers and agricultural systems (Food Agricultural Organisation, 2010; Andrieu et al., 2017). CSA strategies and technologies have been in use in many countries around the world to address climate change issues and to improve economic growth and the growth of the agriculture sector (World Bank et al., 2014). Another concept which recently emerged, and which is often associated with CSA is climate resilient agriculture (CRA). Some authors tend to use these terms interchangeably (Viswanathan et al., 2020). However, CSA is a much broader term that encompasses CRA. It is noted that CRA includes agricultural practices and technologies which enhance resilience and increase the capacity of smallholder farming systems to withstand disturbances from climatic factors and enable quick recovery (Rao et al., 2019). In the context of the present study, the two terms largely overlap since the CSA practices under focus are more toward enhancing the resilience of smallholder farmers than achieving the other CSA goals.

The growing importance of urban and peri-urban agriculture in meeting human and ecological needs is evident in literature (Cofie et al., 2003; Moreau et al., 2012), and so is the urgency for taking measures to ensure the sustainability of these agricultural systems (Dube et al., 2021). In the wake of these observations, the current study seeks to investigate how climate-smart the smallholder agriculture in peri-urban areas of South Africa's Gauteng province is.

STUDY AIM

The aim of this study was to assess agricultural practices by peri-urban smallholder farmers in the Gauteng province of South Africa in order to determine the extent to which the practices are climate smart. The study was intended to produce information which would guide recommendations for sustainable measures required to promote the uptake (or increased adoption) of climate smart farming practices in the study area and other areas with comparable conditions.

STUDY RATIONALE

Agriculture within and around cities is expanding and this makes it important to promote production systems that aim to achieve increased food security, reduced carbon emissions and enhanced resilience to climate change (Moreau et al., 2012). Urban and peri-urban agriculture has historically been making a significant contribution to food availability and healthy diets in many cities in southern Africa (Cofie et al., 2003). A great deal of research on smallholder agriculture in Africa has focused on the impact of climate change on agricultural production and on adaptation strategies used by the farmers. Information about the extent and the impact of CSA adoption in peri-urban areas on the continent and in South Africa in particular is still limited. On one hand, the global challenge of climate change and variability is putting urban and peri-urban agriculture under immense pressure. On the other hand, research shows that appropriate adaptation strategies can enhance the resilience and sustainability of these agricultural systems (Dube et al., 2021). The sustainability of peri-urban agriculture is important considering the critical role this production system plays. Apart from meeting the increasing demand for food in urban areas, urban and peri-urban agriculture provides employment and creates income for the farmers (Anaafo and Akolgo, 2018). It is well-documented that CSA has been implemented in many parts of the world (World Bank et al., 2014). It is of interest to find out at the local scale, the extent of adoption of these technologies and how they are possibly transforming smallholder agriculture.

The present study addresses an important and growing theme in the global context, and which focuses on action to address the United Nations Sustainable Development Goals (SDGs). By addressing challenges of food security and enhancing the resilience and sustainability of smallholder agricultural systems, CSA can address a couple of SDGs, either directly or indirectly. These include SDG 1 (No poverty), SDG 2 (Zero hunger), SDG 13 (Climate action), and SDG 15 (Life on land). The results from this case study are hoped to give insights on existing gaps and what options to take in order to improve the scale of CSA adoption by smallholder farmers in peri-urban environments. The relatively small sample used in this study may however limit the potential to generalize and apply the findings to other peri-urban areas elsewhere.

REVIEW OF RELATED LITERATURE

CSA comprises practices and technologies useful for adaptation to climate change by farmers and helps to increase productivity whilst simultaneously reducing GHG emissions. CSA may also assist governments in achieving national food security as well as reducing poverty (Barnard et al., 2015). CSA practices which are appropriate for enabling farmers to effectively adapt to climate change range from the use of techniques and mechanisms suited for farm-level operations to international policy and finance mechanisms. Examples of such technologies and techniques include agro-forestry, mulching, minimum tillage, crop rotation, water conservation, methane reducing rice systems and soil cover maintenance (Barnard et al., 2015).

It is noted that CSA is not a one-size-fits-all practice or one particular strategy, but an array of practices integrated into an agricultural system at various scales (Thierfelder et al., 2017). It is further noted that there is no CSA blueprint and that its implementation is subjected to a country or community's specific context (Food Agricultural Organisation, 2010). Nagargade et al. (2017) observe that CSA strategies incorporate traditional and innovative practices and technologies relevant to a location's context for the adaptation of climate change. Partey et al. (2018) point out that there are uncertainties around the practice with regard to what technologies and practices should be categorized as CSA and which of the three pillars (productivity, adaptation, and mitigation) should be given priority in any given context.

Lima (2014) identifies some technologies and practices generally used by some African countries. The Democratic Republic of Congo invested in irrigation management, drought-tolerant seed variety production and information dissemination. Strategies implemented by Lesotho include conservation agriculture, soil organic matter management, agroforestry and production of drought-tolerant crops and cultivars. Malawi practices minimum tillage, agroforestry and utilizes herbicides. Mauritius practices a variety of technologies including mixed-cropping, crop rotation, pest control based on indigenous knowledge systems, pit planting, adjustment of planting dates, and the use of rainwater harvesting ponds on the fields. There are a number of CSA practices that have been adopted in South Africa. These include no tillage, crop diversification, crop rotation, intercropping, mulching, management of pest, disease and weed and improved soil fertility (Blignaut et al., 2015; Schulze, 2016).

Despite the wide range of benefits that CSA practices offer to low income and vulnerable farming communities, the adoption of CSA remains a challenge in Africa. Less than 1 million hectares of farmland is under CSA and a greater part of this is implemented by commercial farms (Milder et al., 2011). The lag and lack of CSA in Africa is mostly due to several barriers that hinder adaptation by smallholder farmers. The barriers include a lack of financial resources, infrastructure, skills, or awareness of CSA technologies (Rakgase and Norris, 2015). A majority of smallholder and subsistent agricultural systems are rain-fed and have limited access to technological inputs (Pereira, 2017). Some regions have high population densities and experience land degradation. Such areas tend to lack crop residue and other forms of biomass (that could be utilized for mulching or soil fertility) due to its demand for other purposes such as livestock fodder fuel or construction (Barnard et al., 2015).

Evidence of Changes in Weather and Climate Patterns

Globally, the agricultural sector faces unprecedented changes relating to changes in weather and climate patterns with observable shifts in seasons and rainfall threatening crop yields and the availability of food. Over the past half century, South Africa's temperatures have shown an overall increasing trend although not as steady as the global change (Schulze, 2016) as seen in **Figure 1.**

There is evidence that the Gauteng province of South Africa has generally seen increases of mean maximum as well as minimum temperatures. As noted by the Gauteng Department of Agriculture Rural Development (2017) the province has shown trends of increased temperatures in the period 1931–2015 of more than 2°C/century, which proves to be much higher in comparison to the mean global warming trend in the last century of ∼1°C. This is due to the rapid urbanization of the province leading to an increasing heat island effect (City of Tshwane, 2015).

Production of various types of field crops in South Africa has shown a steady shift in total crop area in response to climate variability. In particular, the crop area under white maize dropped from 1.5 million hectares to 1.1 million hectares (Department of Environmental Affairs, 2016). Further, the production of dryland wheat in the Free State, Limpopo and North West provinces has declined, from around one million hectares in the late 1990s to 200 000 hectares by 2013. The Gauteng province experienced 57 mm less rainfall between 1985 and 2014 which implies a significant effect of climate variability. In addition, the province experienced temperature increases of about 0.5°C which potentially increased the occurrence of droughts (Elum et al., 2017). There was a decline in production of potatoes and cabbages as 77% of potato farmers and 67% of cabbage farmers across the provinces experienced challenges of high/extreme temperature (Elum et al., 2017). It is noted that these trends were experienced due to the lack of risk mitigation measures by the farmers thereby exposing the crops to climatic risks (Department of Environmental Affairs, 2016). This in turn exposed the production and socioeconomic vulnerabilities of farmers in South Africa, particularly of smallholder farmers.

CSA as an Adaptation Option

The Intergovernmental Panel on Climate Change (2007) defines adaptation as the moderation of harm of actual or expected climatic effects or pressures through adjusting natural or human systems. According to Akinnagbe and Irohibe (2014), adaptation involves employing appropriate steps and procedures or adopting necessary adjustments to reduce the effects of climate change. It also involves the exploitation of positive effects. The aim of adaptation is to reduce exposure to risk, improve one's capacity of coping to risks and damage, and to exploit new opportunities.

According to the Food Agricultural Organisation (2010) adaptation to climate change is vital for the achievement of food security and agricultural development goals. Khatri-Chhetri et al. (2017b) note that there are adaptation options that may be utilized to achieve the reduction of climatic risks in the agricultural sector. CSA services, technologies and practices are adaptation options used to increase productivity, enhance resilience to climate variability and to reduce GHG emissions (Khatri-Chhetri et al., 2017b). These options include practices such as minimum tillage,

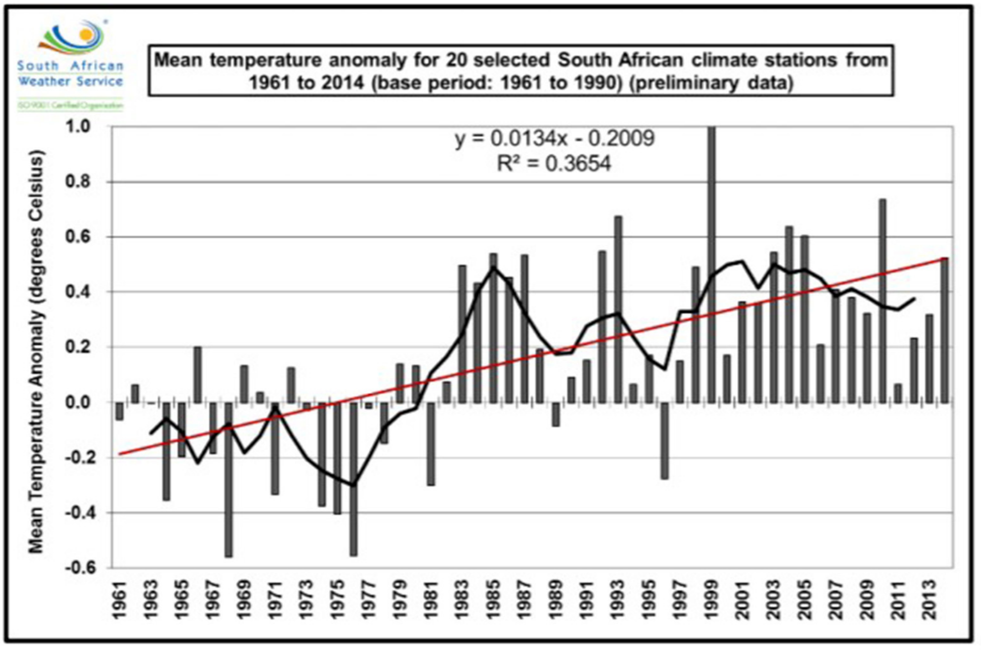

FIGURE 1 | Mean temperature anomaly for 20 South African climate stations from 1961 to 2014 (Source: South African Weather Services, 2015).

FIGURE 2 | Study locations in the City of Tshwane Metropolitan Municipality (Source: Government of South Africa, 2021).

various crop establishment methods, the management of nutrients and irrigation as well as water use efficiency and management.

A study by Finger and Schmid (2007) projected Research has shown that there are increased yields when a change in crop sowing dates combined with the use of irrigation technologies were applied. It also resulted in less variations when compared to the case where adaptation measures were not implemented. Similar cases of farm level studies indicated that crop yields, input use efficiency and net income increased with the adoption of CSA. An on-farm experimental study conducted by Khatri-Chhetri et al. (2017a) across South Asia revealed that the implementation of a single or a combination of technologies had a significant positive impact on rice and wheat yields. For instance, an increase of 83% and 23% of rice and wheat yield, respectively, was realized from the use of nutrient and water management technologies.

The preceding sections have shown that there is a variety of technologies and practices available as CSA options in southern Africa such as conservation agriculture, agroforestry, crop diversification and climate information services (Zougmoré et al., 2018). However, the rate of adoption of CSA practices and technologies remains low despite the associated benefits (Khatri-Chhetri et al., 2017b; Tiamiyu et al., 2017).

The detrimental impacts of climate variability and change on smallholder farming systems can no longer be ignored or denied (Schulze, 2016). It is therefore imperative for farmers to embrace appropriate adaptation strategies to enhance resilience (Mathews et al., 2018). Smallholder farmers are mostly adversely impacted by the occurrence of climate change and may require support from the local / central government or non-governmental organizations. In order to recommend appropriate forms of support, it is important to assess the status of CSA implementation in the given communities. The next section presents the materials and methods used in this study.

METHODS

Study Area Description

The study focused on the City of Tshwane Metropolitan Municipality which lies on the northern part of Gauteng province of South Africa. Gauteng province is the smallest of the nine provinces of South Africa in terms of geographic extent (**Figures 2**, **3**). It is situated in the north-eastern interior of South Africa, occupying 18,176 km^2 or just 1.5% of the countries' land (Statistics South Africa, 2020). The province is made up three metropolitan municipalities, namely, Ekurhuleni, Johannesburg and Tshwane. Gauteng is regarded as the largest urban economy in Africa (Wray and Cheruiyot, 2015) and includes mining and industrial centers as well as pockets of agricultural hubs. Gauteng province is the financial capital of South Africa and the country's economic hub, contributing about 34% of the country's GDP (Statistics South Africa, 2019). It is highly urbanized and houses approximately 15.5 million people or 26% of the country's total population (Statistics South Africa, 2020).

The Gauteng province has about 830,000 hectares of agricultural land, of which, just over half is considered potentially arable and 390,000 ha is suitable for grazing. The province is conveniently positioned for agricultural production, with good infrastructure and access to markets (Gauteng Department of Agriculture Rural Development, 2017).

The agricultural zones in Gauteng province have ∼242,594 agricultural households of which 40,700 rear livestock, 160,700 grow crops and 16,800 practice mixed farming, and only 1,700 (or <1%) are commercial units (Gauteng Department of Agriculture Rural Development, 2017). The sector contributes 0.5% to GDP and 0.5% to employment quotient in Gauteng province.

Research Design

This study adopted a case study design and makes an in-depth study of CSA adoption and implementation in selected areas of the City of Tshwane Metropolitan Municipality. The study adopted a cross-sectional (once-off) approach to collect data and a descriptive approach to answer the questions of what, where, when, who and how, with regard to climate smart farming in the study area (University of Southern California Libraries, 2016). Aspects of both quantitative and qualitative procedures were used; thus the study employed the mixed methods approach (Akhtar, 2016). The research strategy used the qualitative approach to decipher social phenomena from the participant's perspectives, and collected quantitative data relating to the existing agricultural practices by the farmers (Tiamiyu et al., 2017). The study made use of primary data from surveys and field observation as well as secondary information from published sources and unpublished information availed during interviews with key informants.

Data Collection Instruments and Methods

Data collection instruments used in this study consisted of a semi-structured questionnaire, semi-structured key informant interviews, field observations and informal discussions with participants. The semi-structured questionnaire was targeted at smallholder crop farmers as respondents. Face to face engagements were held with thirty-six farmers at their respective farms. Interviews were held with local government officials (in the City of Tshwane Metropolitan Municipality) who were working with the farmers in the four selected locations of Rooiwal, Soshanguve, Mamelodi, and Cullinan. Field observations were conducted to gather supplementary information and to confirm data collected from questionnaires and interviews. Informal discussions were held with participants where appropriate (during field observations), to get clarity or in-depth information on the phenomena being observed.

Sampling Procedure

Purposive sampling was used to select the City of Tshwane Metropolitan Municipality out of the three metropolitan municipalities of Gauteng province. The municipality was selected based on the study purpose and with the expectation that the regions in the municipality presented diverse agricultural activities that would provide unique and rich information relating to ongoing CSA practices. Participants for the key informant interviews were also selected purposively based on their knowledge and experience as extension service providers in the area (Suen et al., 2014). The City of Tshwane Metropolitan Municipality constitutes seven regions, two of which were selected for the study. Simple random sampling was used to select two regions and then to select four locations within the regions selected for study. Cullinan and Rooiwal (situated in Region 5) and, Mamelodi and Soshanguve (situated in Region 6) were the locations selected (**Figure 2**).

The target population composed of smallholder crop farmers operating and residing in the study locations. In order to identify the thirty-six crop farmers who participated in the study, snowball sampling was employed. The sample size was decided on after the data collected became constant and repetitive, when it was realized that a bigger sample would not generate new information or increase the precision of the estimator any further (Saunders et al., 2018; Hennink and Kaiser, 2020). It was deemed unnecessary to continue collecting data after the saturation level had been reached.

Quantitative data on tillage system, crop system, soil fertility management, and irrigation types were analyzed by means of descriptive statistics (frequencies and percentages). Qualitative data generated through observations, semi-structured interviews and open-ended questionnaire items were categorized and subjected to content analysis and categorized into themes that relate to the variables assessed by the close-ended questionnaire items to enable, where appropriate, triangulating the data from the different sources.

STUDY FINDINGS

Agricultural Practices Identified in the Study Area

Information on the practices conducted by the farmers was collected with the objective of assessing the extent to which these agricultural practices were climate smart. The agricultural practices identified in this study can be categorized into four systems: tillage, cropping, soil fertility management and

FIGURE 3 | Gauteng City Regions (Gauteng Department of Agriculture Rural Development, 2017).

TABLE 1 | Farming systems and practices identified in City of Tshwane Metropolitan Municipality.

System	Practices Involved
Tillage practices	- Conventional; - Tractor plowing; - Basin planting; - Hand hoe digging
Cropping systems	- Crop rotation; - Sole cropping; - Intercropping; - Mulching;
Soil fertility management	- Inorganic fertilizer - Organic fertilizer; - Leaf litter; - Animal manure; - No fertilizer
Irrigation methods	- Manual irrigation; - Drip irrigation; - Surface (flood) irrigation; - Sprinklers

Compiled through questionnaire, interviews, and field observations.

irrigation systems. This categorization was adopted from a related study conducted by Makuvaro (2014) in smallholder farming communities in Zimbabwe. **Table 1** identifies the farming systems and the associated practices.

Figure 4 displays the numbers of farmers that practiced each of the various farming systems. The most commonly utilized tillage system was conventional tillage, reported by 15 respondents. Closely next to this was the use of tractors and hand digging utilized by 10 and 7 respondents, respectively. The least utilized approach was the use of plant basins. None of the respondents applied zero tillage in their farms.

There seemed to be no overwhelmingly popular cropping system. The largest proportion of respondents (44%) practiced crop rotation. The second most popular cropping system in terms of respondents implementing it was intercropping, implemented by 28% of the respondents, followed by sole or mono cropping and mulching, each implemented by only 11% of the respondents.

Regarding soil management, the use of inorganic fertilizer was the most utilized approach with close to half of the respondents (47%) indicating constant use. The second most popular soil fertility management was the use of animal manure, indicated by 28% of the respondents. The next was organic fertilizer which was utilized by 17% of the respondents. One respondent indicated the use of leaf litter while two did not apply any fertilizer.

With respect to irrigation systems, drip and sprinkler irrigation were the two most commonly used include with 44 and 33% of the respondents, respectively. About 14% of the respondents used manual irrigation (pouring water using buckets) while 6% used the surface (flood) method. Observations during the study confirmed some of the irrigation methods that

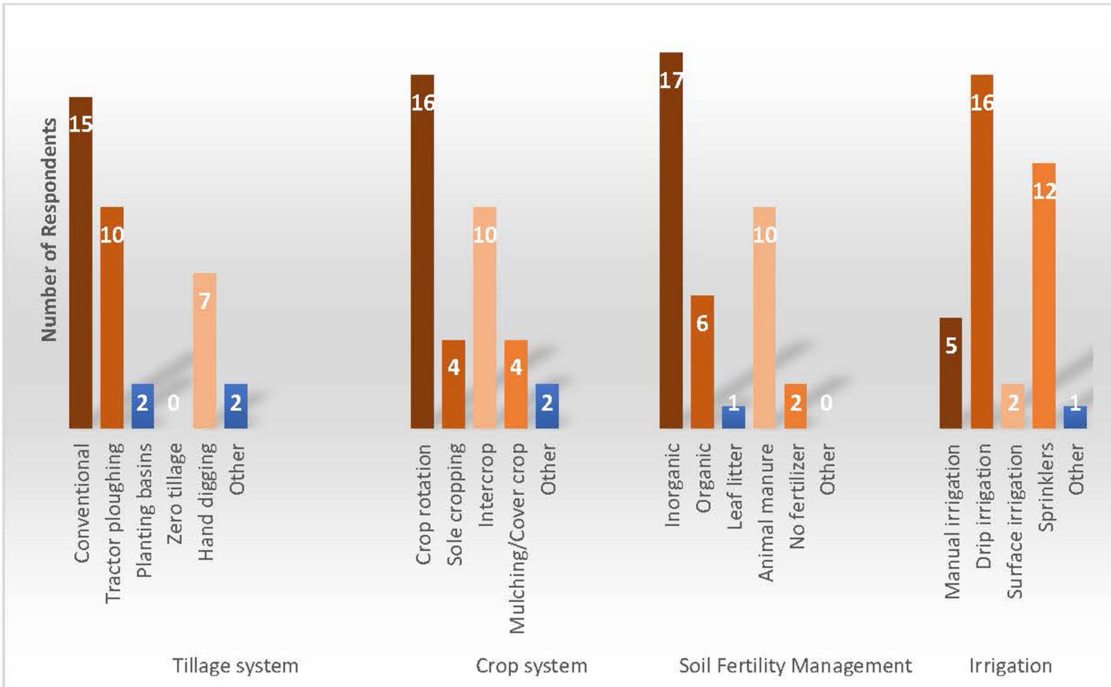

FIGURE 4 | Existing agricultural practices by smallholder farmers in Rooiwal, Soshanguve, Mamelodi, and Cullinan areas who participated in this research. $N = 36$. Multiple responses were allowed.

FIGURE 5 | Drip irrigation in a greenhouse in Soshanguve area (Source: survey results—field observations).

were being used in the area. **Figure 5** presents a picture of drip irrigation observed during this study.

Respondents' Years of Farming Experience

The experience of a farmer is known to influence the decision and choices the farmer makes as well as his/her planning for future mitigation strategies (Elum et al., 2017). To be able to make an informed assessment of the farmers' perceptions and practices, this study investigated the participants' years of farming experience. **Table 2** shows the number of years the farmers participating in this study have been practicing. A greater proportion (47%) of the farmers has been practicing for 11–15 years and 33% has been farming for 6–10 years. About 8% has been practicing for 5 years or less. It was seen that generally farmers who had been practicing for a longer time were more traditional (in terms of methods used) and highly conventional as compared to those new to the field. Such respondents indicated that their indigenous knowledge and skills about farming and adaptation strategies were acquired through generational transfer from their predecessors.

TABLE 2 | Respondents' number of years of farming experience.

Years of farming experience	Number of respondents
0–5	3
6–10	12
11–15	17
16–20	4
Over 20	0

Respondents' Perceptions and Knowledge of Climate Variability and Change Issues

The study explored the farmers' perceptions and knowledge about climate variability and change, the impacts and ways in which the farmers have adapted. The respondents were also questioned about their knowledge of CSA and whether they implemented any CSA strategies. It can be noted that the concept of CSA was explained in vernacular language to ensure the respondents had the same understanding of what practices were implied. The farmers were also asked for their opinions on what they perceived as the most appropriate way forward for the adoption of CSA practices. **Figure 6** presents the findings.

The results indicate that all farmers were aware of the concept of climate change. In general, the farmers expressed that over the years, there has been much less rainfall and higher temperatures, which affect their farming activities. In addition, the farmers showed a general awareness that there has been a change in the starting and ending times of seasons, causing difficulties in planning for cultivation.

Figure 6 shows that most respondents (58%) indicated having experienced the effect of all the climate change indicators or variables on crop health, production and yield. The farmers expressed awareness that temperatures and amount of rainfall received directly affects the soil moisture which determines crop productivity. The study revealed that decision on planting dates was dependent on the available soil moisture as well as availability of seed and draft power.

The findings show that most respondents (61%), perceived awareness campaigns and training regarding CSA practices as the most critical intervention measures to increase adoption of CSA. Above 50% of the farmers had no knowledge of CSA practices. This finding explains why most respondents perceived more awareness campaigns and training on CSA practices as an intervention that could increase adoption of CSA practices among smallholder farmers.

A relatively smaller proportion of respondents (22%) opined that access to credit facilities is important to enhance the capacity of farmers to procure the necessary inputs for climate smart farming. Policy changes to create an enabling environment, training of extension staff and provision of supportive programmes did not seem to be critical measures in this regard. With regard to credit facilities it should be noted however that given the high interest rates charged on loans / credits by banks in South Africa, access to credit facilities *per se* may not be a panacea for the smallholder farmers as they may struggle to pay back the principal amount together with the interest. The interest rates charged by the banks is in lieu of the costs incurred by the banks as they raise the funds at commercial markets (Land Agricultural Development Bank of South Africa, 2021). The lending institutions require collateral security and do make assessment and give loans only to qualifying candidates (Land Agricultural Development Bank of South Africa, 2021). The study revealed that many smallholder farmers fall out and fail to qualify in this regard. Perhaps, the farmers should get access to soft loans with very minimal interest rates and with flexible terms of repayment, including right-off in the event of poor production due to natural challenges such as prolonged drought.

DISCUSSION

Tillage Practices and Cropping Systems

This study revealed that conventional tillage practices (using tractors for cultivation or using hand hoes in cases of inadequate financial resources) were predominantly practiced by the peri-urban farmers under focus. This is despite the known detrimental effects of these systems on soil quality over time (Makuvaro, 2014). Conventional tillage systems are known to promote soil degradation and are not regarded climate smart.

The study also showed that the use of plant basins was not popular in the area. Basin planting is considered a climate smart practice due to its soil erosion mitigation properties and effectiveness and efficiency in harnessing water resources for the crops (Kaczan et al., 2013). These findings indicate that regarding cultivation and soil preparation, farmers had to a greater extent maintained the conventional practices which are not typically climate smart (with respect to the pillars of productivity, adaptation, and mitigation).

Crop rotation appeared to be common knowledge and practice among the farmers and its positive impacts on soil quality was widely appreciated among the farmers. Despite its benefits, the practice was not maximally implemented in the study area. The study revealed that the types of crops and hectarage cultivated was determined by the demand from consumers. This observation is consistent with the findings by Mudhara (1995) in the Chivi communal areas of Zimbabwe that the farmers conducted crop rotations on only 40% of maize fields with other crops such as sunflower, pearl millet and groundnuts due to demand factors.

The second most practiced cropping system in the study area was intercropping. According to Muimba-Kankolongo (2018), intercropping involves mixing a number of subsidiary crops on one field often with one base crop to accord higher yields per unit area. This practice maximizes the use of natural resources such as soil moisture, radiation from the sun, and nutrients due to the various crop shapes, root structures, and physiological components of the crops. It is beneficial for the conservation of good soil quality. Sole or mono cropping, defined as a practice whereby a field is used for cultivation of a single crop type (Muimba-Kankolongo, 2018) was one of the least used practices, with 4 respondents indicating use. This reflects that mono-cropping is not typical of smallholder farming systems except in special cases. An example in this study was a farmer who, due to lack of water resources, cultivated only sunflower plant because it is less intensive with regard to water use and can tolerate short drought periods (Ahmad et al., 2014).

Soil and Water Management Practices

The use of inorganic fertilizer was the highest utilized soil management practice with close to half the respondents indicating constant use. Many farmers referred to 2:3:2 or 2:3:4 fertilizer, depending on requirements of the soil and crops. The first ratio unit refers to the proportion of nitrogen (N), followed by phosphorus (P) and potassium (K). Applying this type of fertilizer on the soil has negative impacts which include emission of GHG's, disruption of soil as development of new aggregates is impeded, and groundwater pollution through the development and leaching of nitrates via mineralisation of soil micro-organisms that release ammonia (Faurès et al., 2013). The study gathered that high usage of inorganic fertilizer was because of financial constraints of smallholder farmers to purchase environmentally friendly soil management technologies. Inorganic fertilizer was perceived to be cheaper and

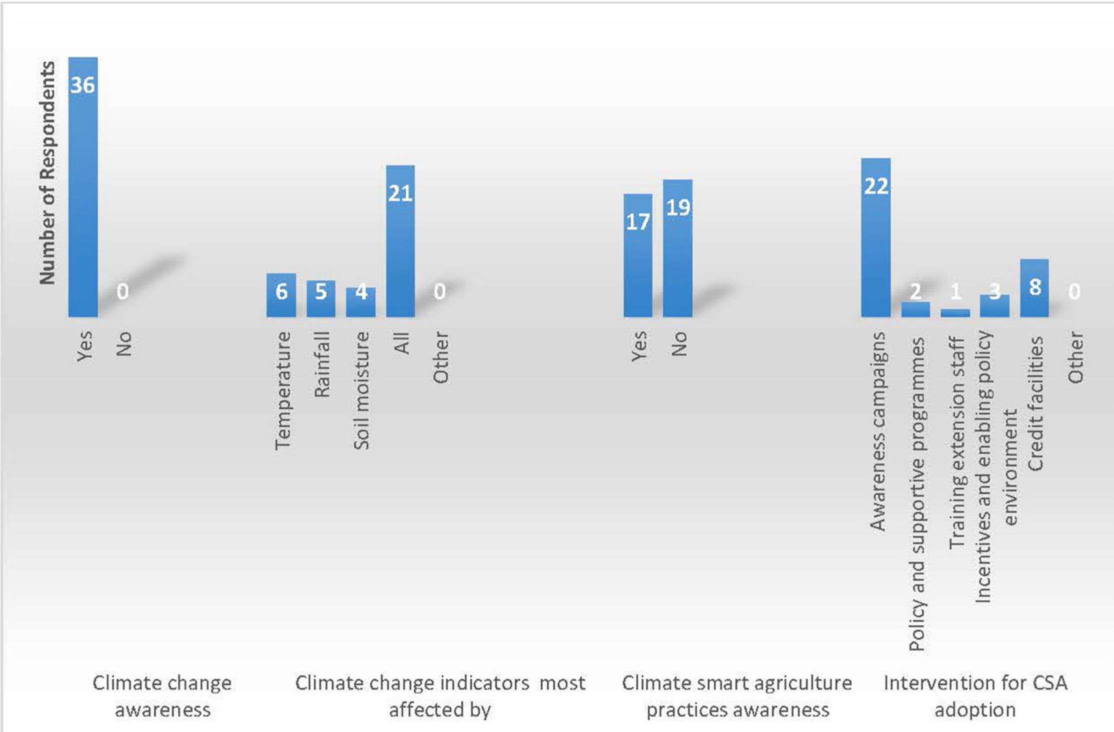

FIGURE 6 | Awareness of climate variability/change and CSA, and perceived interventions.

more effective in terms of yields. According to Hazeltine and Bull (2003), manure and compost are low-strength fertilizers, where 100 kg chemical fertilizer composed of 10-5-10 contains about the same amount of manure N-P-K of 2,000 kg on an average farm.

Animal manure was second in use by the participants in this study. Some farmers used chicken manure from the poultry they were rearing. Some farmers could acquire manure from neighboring farms that were rearing poultry or livestock. In such cases, this implied easier access to relatively cheaper animal manure. Only 6 respondents indicated using humus (organic fertilizer) due to the high costs and expenses of this fertilizer which oftentimes become a liability.

The two commonly used irrigation systems include drip irrigation and sprinklers by 44 and 33% of the respondents, respectively, followed by manual irrigation (14%) which included the use of hose pipes.

Awareness of Climate Change and Adaptation Mechanisms Adopted

There was an overwhelming awareness among the respondents, of climate change and its impacts on crop productivity and yields. The findings in this study concur with the findings by Dube et al. (2021) among peri-urban farmers in Bulawayo, Zimbabwe. The present study confirmed that the farmers have, over time, adapted various ways of addressing the impacts of climate change. Some farmers in this study, mainly those with over 10 years of experience, expressed that the use of indigenous knowledge has enabled them to withstand the challenges of climate change. Strategies used included growing nitrogen-fixing crops (legumes) in rotation and the use of higher soil organic matter which result in reduced use of inorganic fertilizers and reduced demand for water. Other farmers resorted to tilling the soil just before the rains come to enable the soil to hold onto the water for longer periods of time. These results compare well with the findings by Rakgase and Norris (2015) which showed that the perception of older farmers to climate change and its impacts such as drought is critical as they have been highly exposed and have experienced the changing conditions over the years, and have observed the severity of the impacts. Further research is required to verify the conception by the farmers of tilling the land just before the rains since this conception is inconsistent with research findings showing more runoff on occasional strategic tillage plots compared to no tillage treatments (Dang et al., 2018).

Climate Smartness of Agricultural Practices in the Study Locations

Manda et al. (2019) point out that the climate smartness of practices depends on their ability to enhance food security, mitigate against climate change and assist in reducing GHG emissions. However, there is no specific guideline or criteria on what should be included, as CSA includes various practices or technologies making it a challenge to prioritize CSA objectives. Further, there is a lack of a workable method to assess climate smartness of practices as there is limited amount of information available to assess the impacts. According to Bell et al. (2018) the impacts of CSA are the culmination of three outcomes which are the pillars of CSA which include productivity (measured through yield or economics), resilience (measured by means of any factor that has the capacity to buffer a system) or mitigation.

Lima (2014) notes that there are examples of traditional and research-based agricultural practices in every country that can be considered climate smart, however, such are not mainstreamed and do not get adequate support. These include agroecological practices such as agroforestry, mulching, mixed farming, intercropping and growing of drought-tolerant and/or high-yielding crop varieties.

In this study, climate smartness was determined by the potential for the practices to achieve the pillars of CSA, that is, reducing GHG emissions, increasing food security and increasing the resilience of the farming systems against climate variability and change. In a water scarce country like South Africa, and the Gauteng province in particular, practices such as mulching, cover-cropping and crop rotation practiced by the farmers in the four study locations, would be considered climate smart. This is because they act as water conserving practices; improve soil quality, structure and fertility and reduce runoff. These attributes contribute greatly to food security and adaptation to climate variability and change leading to the achievement of the adaptation and food security goals. Manda et al. (2019) arrived at a similar conclusion in a study in the Lushoto community in Tanzania. According to Huyer and Nyasimi (2017), in terms of the adaptation pillar, these practices promote increased water retention which assists in the reduction of crop losses. With regard to mitigation, the practices have the capacity to improve carbon storage in the soil whilst retaining soil moisture. On one hand, this leads to increased productivity enabled by higher soil nutrients while on the other hand, promotes reduction in soil erosion.

This study found crop rotation to be the most frequently used practice among the farmers under focus. The practice of crop rotation is used to address agroecological issues relating to declining soil quality. The practice involves growing plants in sequence on the same land, fostering carbon sequestration. The practice has the potential to reduce Methane (CH_4) and other GHGs emissions, increase crop yields and productivity, reduce soil erosion, increase nutrient cycling and reduce pests and diseases (Singh and Singh, 2017; Partey et al., 2018).

The use of crop varieties by farmers is considered climate smart because it has the capacity to control pests, increase yields and increase drought tolerance. Since the practice accords improved resilience it helps to achieve the adaptation pillar. It also applies to the production pillar, considering the potential to enable high sustainable yields (Huyer and Nyasimi, 2017). In line with this observation, Singh and Singh (2017) confirmed that mixed cropping reduces pests and diseases as well as the risk of crop failure whilst increasing food supply by an estimated 15–20%.

Traditional organic composting including animal and chicken manure enhances the soil organic matter and improves carbon sequestration (Singh and Singh, 2017). This addresses the mitigation and resilience pillars of CSA. A study by Subedi et al. (2019) assessed CSA practices that increase crop yield and compared various soil fertility practices found that in Nepal the application of *jholmal* (which is a mixture of animal manure and water) increased yields of rice by 15.5% and reflected similar results in four other tested sites, as compared to the use of inorganic fertilizers. The most frequently used soil fertility management practice in the current study locations was inorganic (chemical) fertilizer followed by animal manure. The proportions of farmers using organic fertilizers was relatively low (28%), which is concerning.

Irrigation practices were generally minimal in the area under focus. Manual irrigation methods were less popular in the area. The study gathered through key informant interviews that this was because these irrigation methods were labor intensive and not water efficient. The use of the drip system and sprinklers were the most used. The farmers who used these indicated that the practices were convenient and conserve water thus, appropriate in water scarce areas. Key informant interviews revealed that drip irrigation utilizes a lot less water due to its targeted crop irrigating model and was perceived to be economically viable for the low-income farmers under focus. Drip irrigation is an advanced irrigation method characterized by frequent and precise application of water in small amounts through a system of plastic pipes onto the root zone of crops in localized areas (Patle et al., 2020). It assists the conservation of water yielding better returns for farmers' investments (Balana et al., 2017). The irrigation efficiency is up to 90%—depending on the crop and soil types, root depths and weather conditions. Due to these features, drip irrigation is climate smart due to its capacity to create resilience and to mitigate against impacts of climate variability or change. It also has benefits such as increasing crop yields and reducing diseases and bleaching since the application is not on foliage. The use of drip irrigation thus has the potential to enhance food security and improve the farmer's livelihoods (Balana et al., 2017).

Scaling Up Uptake of CSA Technologies and Practices

The term scaling up refers to a variety of processes which are defined in different ways (Makate, 2019). In this study, the term implies horizontal scaling up (also referred to as scaling out) whereby the adoption of CSA spreads across the geographical area with more farmers adopting the technologies. The term also implies vertical scaling up whereby a technology that has been used by one farmer becomes adopted by a group of farmers or association of farmer groups (Makate, 2019). The farmers in this study were employing various adaptation and mitigation strategies in response to climate variability and change even though the level of awareness of the concept of CSA was low. These results compare well with the findings of Knegtel and Naidoo (2014) that some farmers in the city of Durban in South Africa were implementing climate-smart agricultural techniques but they were not aware that such techniques were climate-smart. It is possible that due to limited access to scientific information smallholder farmers may not have knowledge of technical terms such as CSA yet they may possess knowledge of some CSA practices acquired and accumulated over years of experience, often transferred from one generation to another (Horamo et al., 2021). The farmers in the study area were implementing adaptation mechanisms acquired from indigenous systems as well as scientific knowledge acquired through agricultural extension services. However, much more can be done to scale up the uptake of CSA in the Gauteng region in terms of geographical spread of technology adoption as well as more intensive implementation of the adopted technologies. Peri-urban areas are highly vulnerable to climate-related disasters partly due to dwindling traditional informal institutions and the associated forms of collective action and interdependence in these communities (Revi et al., 2014). Therefore, local authorities should consider reviving and empowering local traditional institutions that can help to promote technology adoption in these smallholder farming communities.

CONCLUSION

This study focused on smallholder crop farmers in the peri-urban areas of Tshwane Metropolitan Municipality in Gauteng Province. The findings revealed overwhelming awareness of the impacts of climate variability or change on production and food security. To some extent, the farmers were employing various adaptation and mitigation strategies against these impacts even though the level of awareness of the concept of CSA was low. The study revealed that the non-climate smart conventional tillage practices were predominantly practiced by the peri-urban farmers under focus. Some CSA practices acquired through indigenous knowledge systems or scientific knowledge were implemented in the study area but to a limited scale or intensity. Much more could be done by the local authorities, extension service providers and the farmers to jointly scale up the uptake of CSA in the Gauteng region. The study recommends inter-connected interventions involving traditional institutions, extension service providers and the media to support the farmers. The interventions may include creating capacity development which may involve institutional and financial support for farmers to make the transition to CSA. The study also recommends investments in technology developments and the adoption of inter-sectoral approaches to achieve CSA objectives (Sulaiman et al., 2018). Capacity building by stakeholders in the form of training workshops, CSA information dissemination, one-on-one extension engagements and campaigns to raise the awareness of CSA technologies appropriate to the unique conditions of each farmer are recommended. Various stakeholders which can be involved include government extension staff, farmer associations, the private sector, the public sector and researchers. The study further recommends policy development to support the upscaling of CSA technology adoption in peri-urban areas. This is not to call for the development of a new CSA policy as such but the adjustment of existing policies and improvement of coordination of policies to ensure policy frameworks that are supportive of CSA (Williams et al., 2015).

DATA AVAILABILITY STATEMENT

The datasets presented in this article are not readily available because may require additional ethics clearance to share original data with a third party. Requests to access the datasets should be directed to chitam1@unisa.ac.za.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by UNISA-CAES Health Research Ethics Committee. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

MC: conceptualization, project plan, project supervision data analysis, manuscript writing, and manuscript revision. NZPN: conceptualization, project plan, data collection, data analysis, and draft report writing. Both authors contributed to the article and approved the submitted version.

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Determinants of food security in Nigeria: Empirical evidence from beneficiaries and non-beneficiaries rice farmers of the Kano River Irrigation Project

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Introduction: While the prevalence of hunger decreased globally, it has risen in sub-Saharan Africa in recent years mainly due to rapid population growth, low agricultural productivity, and economic downturns. This study was conducted to examine food security determinants at the household levels among the beneficiaries and non-beneficiaries rice farmers of the Kano river irrigation project in Nigeria.

Methods: Cross-sectional data were used for the analysis while multi-stage sampling technique was used to obtain data from 382 respondents, out of which 217 were project beneficiaries and 165 non-beneficiaries; using a semi-structured questionnaire. Data were analyzed using Household food security index and Logit regression model.

Results and discussion: The results showed that 72.6% of the beneficiaries' households were food secure, against the non-beneficiaries, who had 65.4% food secure households. The findings also revealed that the beneficiaries have 11 and 4% food insecurity depth and severity respectively. Non-beneficiaries, on the other hand, had 17 and 8% food insecurity depth and severity, respectively. Extension contact, farm size, rice output, and educational attainment were the positive determinants of food security. Similarly, determinants that could increase food insecurity identified were; credit constraints and household size. It is recommended that the design of a food security strategy should be multi-dimensional and should encompass social, institutional and economic transformation of small scale farmers. Addressing the identified determinants is also crucial for enhancing the food security status in the study area.

KEYWORDS

agricultural productivity, food security index, unemployment, population explosion, irrigation

1. Introduction

There are four global threats that have significant implications for food security viz; population explosions, global warming, loss of biodiversity and globalization of injustice (Matuschke, 2009). The continent of Africa is not yet on the path to eliminate hunger by 2030 while the prevalence of malnutrition in Africa has risen from 17.6% in 2014 to 19.1% in 2019 (FAO, 2019). Over the years, the question of appropriate food security has remained a critical subject for consideration by many government administrations in Nigeria (Ejikeme, 2017; Osabohien et al., 2020a,b). Small-scale farmers in Nigeria constituted 90% of Nigeria's agricultural output (Ayinde et al., 2020) while the majority of such farmers are not able to feed themselves and other relatives. The low productivity is mainly as a result of fragmented land holding, over reliance on rain-fed agriculture, climate change, low access to input and poor economic base. Some interventions were developed in Nigeria since independence in 1960 to increase crop productivity, generate employment, and ensure food security. Notable among the interventions were: The Green Revolution, Lower Niger River Basin Development Authority (LNRBDA), Operation Feed the Nation (OFN), and regulatory bodies such as the Directorate of Foods, Roads, and Rural Infrastructure (DFRRI) and National Agricultural and Land Development Authority (NALDA). However, many of these programs failed due to weak institutional foundation, corruption, and poor implementation (Aderinoye-Abdulwahab, 2020).

The alarming rise of food insecurity in Nigeria necessitates prompt action. As much as 21.4% of Nigerian families were experiencing acute food scarcity in 2020 (Osabohien et al., 2020a). Similarly, Erokhin and Gao (2020) reported that 50% of the Nigerian population are living below poverty line of 1.9 USD. The Global Food Security Index (GFSI) rating shows that Nigeria ranked 94th out of 113 nations in 2019 with a 48.4/100 score, which puts the country below Ethiopia, Niger, and Cameroon (Ayinde et al., 2020). In addition, Nigeria has overtaken India as the world's most impoverished country (Ayinde et al., 2020). Otekunrin et al. (2019) and Amzat and Aminu (2020) reported that food insecurity in the country is aggravated by rapid population growth; they predicted that Nigeria's population would grow to 400 million people by 2050. The country therefore needs to check her population growth if food security is to be improved.

The Kano River Irrigation Project (KRIP) is one of the pioneer projects established by the Federal government of Nigeria in 1970 (Ahmad, 2018). The project aimed at increasing food production and productivity, improve the beneficiaries' income, provide employment opportunities and reduce food insecurity (Yusuf et al., 2020). The study purposively used rice farmers for the study because rice is cultivated in more than 70% of the cropped area (Wudil et al., 2021). The crop is also one of the most consumed staples in Nigeria (Uduma et al., 2016; Fawole and Aderinoye-Abdulwahab, 2021) while available statistics showed that Nigerians consume more than seven million metric tons of rice in 2020 (Ihedioha et al., 2021). In recent decades however, insufficient local rice production to meet the local consumption has emerged as a significant food security issue (Seck et al., 2012; Matemilola, 2017). Historically over dependence on rain-fed agriculture coupled with low investments in irrigated rice production, makes the country to rely heavily on rice imports to meet growing demand (Uduma et al., 2016). Previous studies have looked at food security from various angles, including government engagement, climate change, and the demand for food and associated resources for human consumption (Ayinde et al., 2020). This study is thus the first attempt at investigating the project beneficiaries' food security situation in order to ascertain the extent to which Kano River Irrigation Project (KRIP) has achieved its set objectives for ensuring food security when compared with non-beneficiaries. The study therefore attempted to answer the following research questions:

1. What is the food security status of both beneficiaries and non-beneficiaries rice farmers of the Kano River Irrigation Project in the study area?
2. What are the determinants of food security situation of beneficiaries and non- beneficiaries rice farmers in the study area?
3. What is the average Kcal of major food items consumed per beneficiaries and non-beneficiaries rice farmers' households in the study area?

2. Literature review

Subsistent farmers who live in rural environments are rather poor and are not able to meet their basic daily needs for sufficient food in developing countries (Akukwe, 2020). Consequently, Nigeria has been listed among the 55 Low Income Food Deficit (LIFD) countries due to the high prevalence of undernourished people living within agricultural households (Ambali et al., 2015). Food security indices have been measured globally using various indicators such as: per capita expenditure on food, food insecurity access scale, food consumption score, per capita food consumption, share of dietary intake and coping strategy index (Ogundari, 2017). Notwithstanding the extensive studies on food security indicators, there is still not a consensus on the core parameters that are needed to adequately measure household food security situations at both the micro and macro levels around the world (Akukwe, 2020).

Food security and insecurity are two opposing terms used to describe how much access or lack of access to sufficient and nutritious food are available to a population. Food security involves food access, availability, use and sustainability (FAO, 2017); hence, people can be said to be food secured when they are able to get adequate, safe and nutritious diets all year round. Although, majority of the food in-secured are domiciled in developing countries, food security has become an issue of top priority for both developing and developed countries (Mohammed et al., 2021). This is because household food insecurity is responsible for a huge proportion of malnutrition and deaths in developing worlds (Drammeh et al., 2019); hence the emphasis on food security in the sustainable development goals (SDGs). Moreover, evidence has shown that food insecurity is closely related to socio-economic characteristics such as: poverty, low income, employment status, age, household size, level of education among others (Drammeh et al., 2019; Mohammed et al., 2021; Fikire and Zegeye, 2022). In addition, it has been established that an increased level of education can translate into higher level of food security (Mohammed et al., 2021).

The poorest countries of the world are found in Africa while they face chronic poverty and food insecurity (Farzana et al., 2017). In the same vein, these countries are heavily dependent on rain-fed agriculture and this predisposes the region to environmental hazards such as droughts, desertification, erosion and many others. Consequently, countries have had to develop a range of coping mechanisms to either cushion the effect or strengthen their resilience to household food insecurity. Literature has identified diverse coping strategies applied at the household level amongst population affected by natural calamity such as droughts and erosion (Farzana et al., 2017; Drammeh et al., 2019; Mohammed et al., 2021). Of particular reference is the construction of several dam projects to alleviate issues of droughts and erosion in typical rain-fed agriculture areas of sub-Saharan Africa. Understanding the coping measures that have been put in place at household level in each location is a critical strategy to formulating and implementing appropriate policies that would strengthen food security in those areas.

More farming households would experience severe food insecurity due to the negative impact of the COVID-19 pandemic as enormous challenges are still faced by people with less wealth, lower and more unstable incomes and poorer access to critical basic services (FAO, 2021). The African continent has witnessed the most severe food insecurity while regions such as the Latin America and the Caribbean have not been excluded from the impacts; albeit at a slower pace. The prevalence of food insecurity slightly reduced in Asia between 2020 and 2021. Nonetheless, the pandemic has further amplified the uncertainty characterizing the estimates of the number of people who are affected by food insecurity (Aderinoye-Abdulwahab and Abdulbaki, 2021).

The determinants of food insecurity can be broadly categorized into social, economic, environmental, political and physical factors. Countries have become more food insecure as a result of factors such as: droughts, land degradation, population explosion, lack of productive resources, insufficient assets, poverty and deprivation (Fikire and Zegeye, 2022). Food insecurity has been and remained a public health threat that needs to be addressed in order to reduce environmental hazards and problems of malnutrition, dietary diversity needs and psychological dysfunction (Drammeh et al., 2019). Studies on determinants of food security have been conducted across the world and they range from socio-economic, institutional, environmental, and safety-related perspectives. In focusing on a more precise approach, this study concentrates more on the socio-economic determinants at the household level and economic indicators at the macro level to uncover the determinants of food security among the beneficiaries of KRIP. Whilst Cheema and Abbas (2016) identified that off-farm income significantly impacts household food security positively, Karki et al. (2021) reported that assets possession is an important determinant of food security. In a similar vein, Firdaus et al. (2020) showed a positive association between household food security and socio-economic indices such as: family size, land size and land quality while Fikire and Zegeye (2022) also noted that age is a significant socio-economic consideration in food security index. This is because the older a farmer becomes, the more experience they must have acquired in farm operations and planning; and this will make it easier for them to attain food security. Gundersen and Garasky (2012) had previously asserted that a positive correlation exists between age of household head and food security while food security also increases with increasing income.

Obayelu (2012) in his study on food security situation in northern Nigeria found that only 16% of the households were food secure (FS), 36% food insecure without hunger, 28% FS with moderate hunger and 21% food insecure with severe hunger. His result further revealed that geographical location, food dietary diversity, level of education, occupation of household head, household dependency ratio, social capital and agricultural land-holding size significantly affect households' food security status. Ajayi and Olutumise (2018) found that 43% of their respondents in Ondo State, Nigeria were food secured. The shortfall and surplus indices were found to be 0.13 and 0.20 respectively. Their findings further revealed that experience, education, access to credit, access to extension agent, distance to farm and farm size were the factors that influenced food security in the study area. Akukwe (2020) analyzed food security in agrarian community of south eastern Nigeria where it was shown that majority (53.5%) of the households were food insecure while 46.5% were food secured. The regression coefficients revealed that households headed by unmarried persons with higher level of education and monthly income as well as with fewer dependents were more food secure; while food security decreased with increasing distance to market in southeastern Nigeria. Abdelhedi and Zouari (2020) argued that family farming play a crucial role in the fight against food insecurity in developing countries. They observed that this type of agriculture helps to meet the subsistence needs and generate income for the poor and, on the other hand, contributes to a healthy and balanced diet. Abdelhedi and Zouari (2020) further showed that agricultural value addition positively and significantly impact on food security. Martin-Shields and Stojetz (2019) in their review on the nexus between food security and conflict opined that conflict is the most significant driver of food insecurity in many parts of Africa. Several studies outlined negative correlation between increase in temperature and reduction in rainfall on food security in Africa (Durodola, 2019; Leisner, 2020; Dino Abdula, 2021; Kogo et al., 2021). Climate adaptation strategies such as sustainable watershed management activities, crop diversification, planting of early maturing variety and irrigated agriculture were recommended to assuage the negative impact of weather events on food security (Dino Abdula, 2021).

Household food insecurity has been linked, with a considerable negative correlation, to education level of the households' head, lack of physical assets and absence of female-headed families in Kolkata, India (Maitra and Rao, 2014). Oke (2015) in his study found a negative correlation between food security and population growth in Nigeria. It was also found that increase in productivity; either in terms of a rise in production or expansion of cultivated lands, will positively influence food security at the macro-level (Pieters et al., 2013). Moreover, foreign direct investment in agriculture sector equally has positive impact on food security (Slimane et al., 2016) while it was also observed that the unemployed are 8% and more likely to be food insecure when compared to employed persons.

3. Methods

This section highlights the study area, methods of data collection and the analytical techniques used for data analysis.

3.1. Study area

Kano State is located between latitude 12° 00' 0.43" North of the equator and longitude 8° 31' 0.19" East of Greenwich (Figure 1). The state has about nine million people with 4,957,952 men and 4,453,336 women (National Population Commission (NPC), 2006). Annual growth rate is estimated at 2.27% (Raimi et al., 2020) and this puts the population of the state in 2020 at 13,895,103 people. The project area is situated in a vast area of over 25 km south of Kano city and is one of the functional irrigation schemes in the country. It is designed to provide irrigation facilities to about 22,000 hectares of land utilizing water release from the Tiga dam through the Ruwan Kanya reservoir (Wudil et al., 2021). The scheme operates in three local government areas: Kura, Garum Mallam, and Bunkure. Data for this study were collected from all the three local governments' areas (LGAs). Due to the lack of baseline data and the limitation of "before and after" approach of not incorporating the counterfactual effect, the study used the "with and without" approach to capture the counterfactual effect.

3.2. Sampling procedure and sample size

The study's respondents included both irrigation project beneficiaries and non-beneficiaries who lived in the same catchment in the study area. Private irrigation schemes that are owned by individuals who can afford were used as non-beneficiaries. With this category of irrigation scheme, farmers use tube-wells and they allow other farmers to use it at a cost. Multi-stage Sampling Procedure (MSP) was employed in assembling data. In the first stage, all three LGAs where the beneficiaries are located were purposively selected due to the presence of irrigated agriculture and high rice production. The second stage of the sampling technique took place at the village level. A visit to the villages in the three project areas- Kura, Bunkure, and Garum Mallam LGAs, was made in order to get a comprehensive picture of the prevailing situation regarding irrigation in the study area. Twenty-four villages were purposively selected for the study, 12 from the irrigation command area and 12 from the non-command site. The 24 villages were purposively selected because of high populations of rice farmers and massive production of rice too. The areas were selected also to ensure an even representation of all towns in the location. The third stage was a proportionate random sampling of rice farmers' beneficiaries (217) and non-beneficiaries (165). Thus, 382 beneficiaries and non-beneficiaries were interviewed as the study's sample size (Table 1). However, out of the 382 interview schedule conducted, only 208 from beneficiaries and 152 from non-beneficiaries were meaningful and were therefore processed for analysis.

3.3. Model specification

3.3.1. Household food security index

The study used the Food Security Index (FSI) and simple statistical techniques. The instrument has been used in Nigeria (Ahungwa et al., 2013); in Ghana (Kuwornu et al., 2013) and in Pakistan (Bashir et al., 2012). It was demonstrated that data on the caloric content of commonly consumed foods were collected using parameters that convert edible portions into calories. The food security indices were constructed and the caloric acceptability was calculated by dividing the calorie supply for the household by the family size adjusted for adult equivalent (Runge-Metzger, 1993). The SPSS Statistical software; version 21 was used to calculate the frequency, mean, standard deviation and other food security metrics (Ahungwa et al., 2013).

$$Z_i = \frac{Household' s\ daily\ per\ capita\ calorie\ avaibility\ (A)}{Household' s\ daily\ per\ capita\ \ calorie\ requirement\ (R)} \quad (1)$$

Where Z_i denotes the status of i^{th} household food security ($Z \geq 1$ food secure and $Z<1$ food insecure).

A household is considered a collection of persons living together and consuming from the same pot. The study used the FAO recommended daily caloric intake of 2,700 kcal for an adult aged man (30–60 years) as a benchmark for developing nations (Kidane et al., 2005) and as a criterion for food security status. Using the shortfall/surplus index, P, numerous food security indices were computed based on Z:

$$\mathbf{P_i} = \frac{\mathbf{1}}{\mathbf{M}} \sum_{\mathbf{i=1}}^{\mathbf{M}} \mathbf{GK_i}. \quad (2)$$

Where $\mathbf{P_i}$ denotes the shortfall or surplus index for the i^{th} household,

$\mathbf{GK}= \frac{\mathbf{X_{ki}-I}}{\mathbf{I}}$ = shortage or excess encountered by i^{th} household,

X_{ki} = Mean everyday caloric accessible to the i^{th} household.

M = the magnitude of households that are food secure (excess index) or food insecure (deficit index).

I = the food security line (2,700 kcal/capita/day).

$$\text{The Headcount ratio (H) is given as } H = \frac{\mathbf{1}}{\mathbf{M}}. \quad (3)$$

Where M = the number of food secure or insecure members of the sampled population

N = total population under study.

With this approach, the individuals or households were aggregated into food secure and food insecure populations. Thus, food poverty was regarded as a condition where an individual's or household's consumption falls below an *ex-ante* identified food security line, in this case (2,700 kcal/capita/day).

3.3.2. Logit regression model for determinants of food security

The binary logistic regression methodology has been employed in several agricultural, economic and extension studies that call for the research and prediction of a dichotomous outcome such as fertilizer use or non-use, adoption and non-adoption, participant and non-participant. The logistic probability model (Bogale and Shimelis, 2009) is expressed implicitly as thus;

$$P_i\left(Y = \frac{1}{X_i}\right) = f\left(Z_i\right) = \frac{1}{1 +^{-(\alpha\ + \beta_i X_i\ +\ \varepsilon_i)}} \quad (4)$$

Where

P_i = *probability that a household is food secure in the face of exogenous variables* (X_i) *and* P_i *ranges between 0 and 1*

e = natural logarithm base

X_i = *a vector of predictor variables*

α *and* β_i = *the regression factors to be predicted, and*

ε_i = *Random error term*

The model is transcribed in expressions of odds and log of odds for simplicity of presentation of the coefficients. As a result, the odds ratio is the ratio of the likelihood of a home being food secure (Pi) to the likelihood of a household not being food secure (1-Pi).

Thus,

$$e^{z_i} = \frac{P_i}{1 - P_i} \quad (5)$$

Local government Area (LGA)	Beneficiaries villages	Sample frame	Sample size (5%)	Non-beneficiaries villages	Sample frame	Sample size 5%
Kura	Karfi	650	28	Gundutse	342	15
	Kura	840	36	Danhassan	397	17
	Bugau	280	12	Kudani	420	18
	Kosawa	590	26	Kosawa	384	17
Garun Mallam	Mudawa	274	12	G/Mallam	164	7
	Chiromawa	337	15	Kwarin bototo	592	26
	Yada kwari	196	8	Garin Babba	174	8
	Kadawa	207	9	Kwanar Gafan	269	11
Bunkure	Bunkure	724	31	Barkun	369	16
	Lautaye	323	14	Kumurya/Daba	228	10
	Gafan	404	17	Karwan Kwari	324	14
	Turba	209	9	Luran	149	6
Total		5,034	217		3,812	165

Source: Authors' computation, 2020.

$$\ln\left(\frac{P_i}{1-p_i}\right) = z_i \quad (6)$$

$$Z_i = \alpha + \sum_{1=0}^{n} \beta_i X_i + \varepsilon_i \quad (7)$$

By introduction of a dichotomous response variable, $Y_i, Y_i = \begin{cases} 1 \text{ if } Y^* > 0 \\ 0 \text{ otherwise} \end{cases}$

Where 1 = food secure

0 = food insecure

i = number of respondents

Solving for the probability that Y = 1,

Equation (5) can be modified as:

$$\left(\frac{P_i}{1 - P_i}\right) = e^{z_i} \quad (8)$$

$$\text{Then, } P_i = \frac{e^{z_i}}{1 + e^{z}} \quad (9)$$

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4. Results

This section presents the findings of the research objectives under the listed sub-headings.

4.1. Household food security of beneficiaries and non-beneficiaries

The summarized data and food security indices amongst the sampled beneficiaries are presented in Table 2. The results showed that 72.6% of the household beneficiaries were food secure, while 27.4% were food insecure based on the necessary daily calorie intake of 2,700 kcal. The data also revealed that beneficiaries' average per capita calorie intake was 2,274.93 and this is lower than the recommended average of 2,700 Kcal. Food secure households consumed 3,607.63 Kcal on average, which was greater than the recommended mean. Beneficiaries' food insecure households consumed 1,625.81 calories per day which translates to 60% of the recommended national average. The food insecurity gap/surplus Index (P), which evaluates the degree to which families deviate from the food security line, revealed that the secure food home surpassed the necessary average Kcal by 34%. In comparison, the food insecure household fell short by roughly 40%. However, the average household size (adult equivalent) for the project was 10 people while it was about 6–7 persons for the food secured households among them and around 13–14 for those who were food in-secured (Table 2). This further showed that the households that were food in-secure had more dependents to their detriment.

On the food insecurity depth and severity, the project beneficiaries had indexes of 0.11 and 0.04, respectively, meaning that there was 11 and 4% chances of food insecurity occurrence and severity among the beneficiaries (Table 2). The food security indices among the sampled non-beneficiaries showed that 65.36% were food secure while 34.64% were food insecure. The data also revealed that the non-beneficiaries' average per capita calorie intake was 2,697.44 Kcal which is slightly lower than the recommended national average of 2,700 Kcal. The average calorie consumption of food secure households was 3,982.69 Kcal; a value that is greater than the national recommendation. Food insecure households consumed 1,323.72 Kcal, which was only 49% of the recommended national average. The food insecurity gap/surplus Index (P), which evaluates the degree to which families drifted from the food security line revealed that non-beneficiary households were short of food security by a margin of 51%. However, the average number of dependents for the food secured among the non-beneficiaries of the project was 7.96 while that of the food-insecure households was 13.98; bringing the overall average of total dependents of sampled households to 10 dependents.

On the food insecurity depth and severity, the non-beneficiaries had indexes that included 0.17 and 0.08; translating into 17 and 8% chances of food insecurity occurrence and severity respectively. Figure 2 presents a graph of the food insecurity index of the beneficiaries and non-beneficiaries. The chart depicted that all the indexes of the beneficiaries were lower than those of the non-beneficiaries.

4.2. Determinants of household food security status of beneficiaries and non-beneficiaries

The study investigated the factors that influence food security in the study area. The dummy variable (food security status) of rice farmers in the project and non-project areas was taken as the dependent variable. The independent variables used were age, agricultural experience, access to credit, educational status, household size, farming output, extension contact, and annual income. The factors of food security status of KRIP beneficiaries are detailed in Table 3.

The estimated logistic regression model indicated that the statistical parameters that express the goodness of fit of the model for the study were highly significant at 1% probability level. The chi-square (X^2) 115.223 and 108.36 for beneficiaries and non-beneficiaries, respectively, indicated support for the model and implied that the model, including the intercept and the explanatory variables, were within the acceptance region. The Cox and Neglekerke estimate (Table 3) of beneficiaries showed that the model's differences between 42 and 61% variance were attributed to the independent variables' contribution in the analysis. For the non-beneficiaries, the estimated Cox and Neglekerke suggested that between 52 and 69% variance observed in the model attributed to the independent variable included in the model. The 2log-likelihood of 129.706 and 98.5 for the beneficiaries and non-beneficiaries, respectively, further confirmed the validity and reliability of the estimated Cox and Neglekerke indicated that model in explaining the statistical influence of the selected variables.

The variables that were positively related to beneficiaries' household food security status were; extension contact (1.1407), farm size (1.263), farming output (1.145) and educational attainment (1.099) (Table 3). The Exp. (β) in parentheses indicated that 1% increase in each of the variables increases the probability of the household to be food secure by the respective Exp (β) coefficient. The age of the head of the household, household size, and credit constraints had negative coefficients which imply that an increase in any of these will result in a decrease in the level of food security. Furthermore, household size also had a negative significant coefficient of 0.452 and Exp (β) of 0.637.

For the non-beneficiary households, farming experience, farm size and educational attainment were positively and significantly related to food security status. Farm size has Exp (β) of 1.712 while the coefficient of educational status of the respondents was positive and significant at 5% level of probability with Exp (β) of 1.13. Credit constraint (−1.093) and household size (−0.452) were negatively significant at 1%.

4.3. Average Kcal of major food items consumed per household per day

The food security index was calculated based on detailed food items consumed by the households within the week. Food items identified for the estimation were cereals (rice, maize, sorghum, millet, and wheat), root and tubers (cassava, yam, and potato), legumes (cowpea, soybeans), poultry,

TABLE 2 Summary of the food security indices for project beneficiaries and non-beneficiaries.

Food security indices	Project beneficiaries			Project non-beneficiaries		
	Food secure	Food insecure	All	Food secure	Food insecure	All
Percentage of households	72.6	27.4	100	65.36	34.64	100
Number of household	151	57	208	99	53	152
Household size (Adult equivalent)	6.78	13.92	10.35	7.96	14.19	11.08
Food security index (z)						
Mean	1.79	0.72	1.18	2.32	0.61	1.70
Per capita daily calorie availability	3,607.63	1,625.81	2,274.93	3,982.69	1,376.28	2,697.44
Food insecurity gap/Surplus index	+0.34	−0.40			0.49	
Head count ratio	0.73	0.27			0.35	
Food insecurity depth	-	0.11			0.17	
Severity of food insecurity		0.04			0.08	

Source: Field survey, 2020.
FIGR, Food Insecurity Gap Ratio; FID, Food Insecurity Depth.
FIGR, multiplying the head count ratio by the square of the food insecurity gap; FID, multiplying the food insecurity gap by head count ratio.

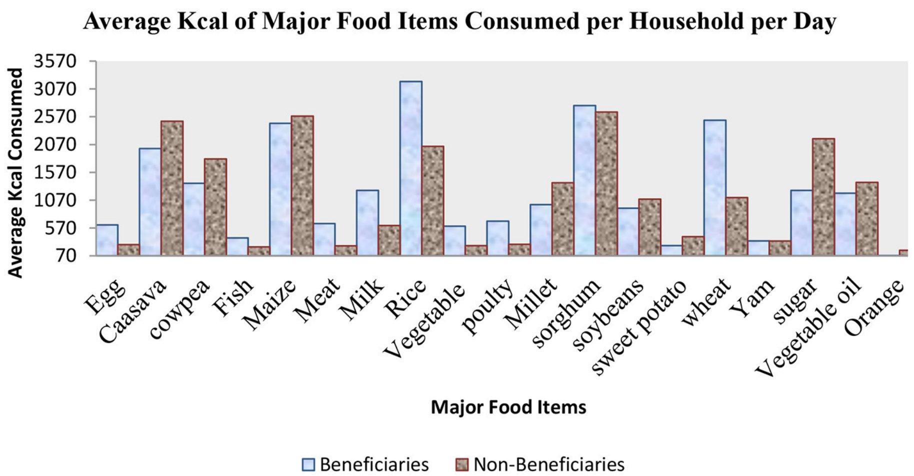

FIGURE 2
Average Kcal of major food item consumed per household per day between beneficiaries and non-beneficiaries. Source, Authors' computation, 2020.

meat, sugar, cooking oil and vegetables. Figure 2 provided information on the major food items consumed by the beneficiaries and non-beneficiaries with the mean Kcal consumed per day.

Figure 2 shows different food groups for households, along with their average Kcal consumption score in the study area. Evidence, as depicted in Figure 2, showed that rice is consumed the most given the amount of kcal consumption per household per day among the beneficiaries. This is followed by sorghum, wheat, and maize respectively; unlike millet which has the lowest amount of kcal consumption and is the least consumed. Among root and tubers, cassava was the highest consumed while the non-beneficiaries consumed sorghum more than other food items as results showed that it had the highest calorie consumption with a mean of 2,654.61 kcal per household. This is followed by maize, cassava, sugar, and rice in terms of consumption pattern of the non-beneficiaries.

5. Discussion

5.1. Household food security of beneficiaries and non-beneficiaries

The finding which indicated a positive relationship between food security and household size is consistent with many empirical studies that affirmed a positive correlation between food insecurity and household size (Jabo et al., 2017). On food insecurity depth and severity, results showed that both beneficiaries and non-beneficiaries were food secured although the project beneficiaries fared relatively better. These results are consistent with other studies where it was reported that 44, 37, and 34% of the households in Lagos, the North Central region and Borno States of Nigeria were food secured (Ahmed and Naphtali, 2014). Similar to these findings, Omotesho et al. (2016) reported that about 67% of households were food secure in Kwara State, Nigeria. Mannaf and Uddin (2012) in their research

TABLE 3 Determinants of food security status of project beneficiaries and non-beneficiaries.

	Beneficiaries					Non-beneficiaries				
Variables	B	S.E	Wald	Sign	Exp (B)	B	S.E	Wald	Sig	Exp (B)
Constant	1.895	1.724	1.208	0.272	6.651	5.919	2.510	5.560	0.018***	371.995
Age of the farmers	−0.028	0.038	0.549	0.459	0.972	−0.042	0.029	2.039	0.153	0.959
Educational status	0.095	0.048	3.891	0.049**	1.099	0.124	0.050	6.188	0.013***	1.132
Farming experience	0.070	0.034	4.151	0.042**	1.073	0.068	0.032	4.575	0.032**	1.070
Household size	−0.452	0.073	38.483	0.000***	0.637	−1.867	0.541	11.886	0.001***	0.155
Credit constraints	−1.093	0.529	4.263	0.039**	0.335	−1.742	0.630	7.654	0.006***	0.175
Annual income	0.000	0.000	0.380	0.538	1.000	0.000	0.000	2.020	0.155	1.000
Rice output	0.135	0.046	8.502	0.004***	1.145	0.043	0.037	1.305	0.253	1.044
Extension contact	0.342	0.592	0.333	0.564	1.407	0.302	0.690	0.191	0.662	1.352
Farm size	0.234	0.137	2.917	0.088*	1.263	0.537	0.250	4.624	0.032**	1.712
Model statistics										
−2loglikelihood	129.706					98.573				
Cox and snell estimate	0.424					0.512				
Neglekerke estimate	0.614					0.686				
Model chi-square	115.223					108.361				

Source: Field survey, 2020. ***Significant at 1%; **ignificant at 5%; *Significant at 10%.

conducted in the Bogra District, Bangladesh reported that 66.67% of the respondents were equally food secured.

5.2. Determinants of household food security status of beneficiaries and non-beneficiaries

Extension contact, farm size, farming output and educational attainment showed positive inclination to household food security. These findings are consistent with that of Ahmed et al. (2017) who reported that outputs and educational attainments were important productivity variables that played essential role in improving household food security. Ogundari (2017) also reported that farm size plays a vital role in agricultural production, poverty alleviation and food security. The age of the head of the household, household size, and credit constraints had negative coefficients. For example, as credit constraints increases, food security will also decrease. The result further indicated that age has a negative correlation with food security. The negative co-efficient was in line with the a-priori expectation that as the number of dependents in the household increase, food requirements will also increase, and more pressure will be on the already scarce resources. A large household with many dependents has more people to cater for and would be more likely to be food insecure. It has been similarly reported that farmers who struggled to access credits equally found it harder to pay back; these set of farmers were necessarily more prone to being food insecure (Amanullah et al., 2019).

For the non-beneficiary households, farming experience, farm size and educational attainment were positively and significantly related to food security status. This indicates that a 1% increase in the farm size could increase the probability of the household being food secured. This implies that an increase in the level of education can increase the food security status of the farming households. This result was in line with a priori expectation that education has a positive correlation with food security, and this corresponds with the finding of Mohammed et al. (2021) who opined that education was an insulator against food insecurity. Years of farming experience was also positive and statistically significant, indicating that the probability of food security for farming households increases with farming experience.

Credit constraint and household size were negatively significant. This means that food insecurity increases with an increase in any of these variables given their corresponding coefficients; as similarly reported that Pakistan's food insecurity is exacerbated by low production due to credit constraints, lack of financial resources and low incomes (Khan, 2021). The finding was also consistent with the assumption that large sized households will be more prone to food insecurity than small sized ones.

5.3. Average Kcal of major food items consumed per household per day

That rice is the most consumed is not surprising as people in developing countries favor consumption of cereals such as wheat and rice over more coarse cereals like millet. It therefore means that there is an urgent need to increase production of the preferred cereals in order to meet domestic demands. The protein-rich crops like beans and soybeans has higher kcal consumption than meat, fish, eggs, and poultry; probably because they were relatively cheaper since farmers typically produce them on their farms. Among root and tubers, cassava was the highest consumed and this could be attributed to its simplicity in preparation as it can be boiled and consumed with grinded groundnut cake. This finding is consistent with that of Lawson (2015) who reported that families in Nigeria greatly depend primarily on products from grains and root/tuber crops. The author further claimed that grain provides calories (46%) and proteins (52%) when consumed while root crops/tubers only offer 20% of calories and around 8% of proteins. On the other hand, non-beneficiaries consumed sorghum more than other food items; but this is closely followed by maize, cassava, sugar, and rice in terms of consumption pattern. The high consumption of sugar and cooking oil by both the beneficiaries and non-beneficiaries may probably be due to culture of the people of northern Nigeria or increased incomes or both.

6. Conclusion and recommendations

This study assessed the food security situation of rice farmers in the KRIP with the aim of exploring the determinants of food security among beneficiaries and non-beneficiaries in the project area. Findings showed that 73% of beneficiaries were food secure when compared to 65% of non-beneficiaries. The beneficiaries' food insecurity headcounts, depth, and severity were 0.27, 0.11, and 0.04, respectively, meaning that 27% of the beneficiaries fall below the 2,700 Kcal per person per day food security adult criterion. The chances of food insecurity incidence and severity were 11 and 4%, respectively. For non-beneficiaries, the food insecurity headcount, depth, and severity index were 0.35, 0.17, and 0.8, respectively. The determinants of household food security at the household level were; extension contact, farm size, rice output, educational attainment, credit constraints and household size. Similarly, at the country level, the result showed that unemployment and population increase had an increasing effect on the prevalence of hunger as well as a decreasing effect on the GDP.

The government should emphasize on creation of awareness and motivation for rice farmers to increase their production so that food security can be further enhanced. This is critical to reduction of poverty and food insecurity. Social networking and collaboration among smallholder farmers is also essential so that they can team up to produce a formidable voice to make demands from authorities. Similarly, to eradicate hunger and food insecurity in Nigeria, government and other stakeholders should emphasize on education and training and provision of enabling environment for investors. All of these will reduce unemployment rate and enhance productivity. Findings from this study might serve as a benchmark for future comparisons with other similar projects targeted at attaining food security.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/supplementary material.

Ethics statement

The studies involving human participants were reviewed and approved by Faculty of Agriculture Ethics Review Committee, University of Ilorin, Nigeria. The patients/participants provided their written informed consent to participate in this study.

Author contributions

AW and SA-A were responsible for the Introduction and Literature Review sections while AA, HM, and HR handled the methodology and results segments. In addition to producing the manuscript, AS and SA-A proof read the article while SA-A prepared it for submission. All authors collectively worked to produce this manuscript and contributed to the discussion of the findings. All authors contributed to the article and approved the submitted version.

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.

Publisher's note

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