

Unpacking innovation demands for climate-resilient mixed farming systems in sub-Saharan Africa: A case of northern Ghana

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Abstract

According to the United Nations (n.d.), climate change is the long-term shift in temperatures and weather patterns due to natural changes, such as the sun's activity and significant volcanic eruptions,

or human activities, such as burning fossil fuels like coal, oil, and gas. The effects of and challenges caused by climate change on farmers' ability to manage mixed farming systems in sub-Saharan Africa are well documented in the literature. However, the synergies among mixed farming systems' components and farmers' innovation demands and responses to climate change impacts remain fragmented. Using a case of mixed crop-livestock-tree

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(MCLT) systems in northern Ghana, this paper examined farmers' responses, their innovation needs, and how these innovations can be catalyzed to enable more farmers to adopt similar climate change adaptations. Our findings show that climate change impacts mixed farming systems in several domains, with these impacts being more visible in some domains. Significant productivity declines are observed in crops, livestock, and the whole mixed farming system. Productivity declines lead to decreased incomes, food availability, and household food security. Female farmers' access to production factors, resource management, and market participation is reduced. Farmers make technical, managerial, and business changes in response to climate change impacts. Such changes are dominated by technical changes, including using high-yielding, disease-resistant, and early-maturing crop varieties, crop and animal pest and disease management, agricultural water and land management, and wind and bush fire control. Interconnections between the MCLT system components include cross-component investments, additional income generation, animal feeding and healthcare improvement, nutrition exchanges, and family nutrition improvement. These interconnections generate income and cash flow and support food and nutrition security, enabling farmers' adaptation. Climate-resilient innovation bundles to enable farmers' adaptation include good agricultural practices, circular farming techniques, irrigation packages, information services, and value-chain linkages. Scaling climate-resilient innovations in northern Ghana and other sub-Saharan African contexts require multiple pathways, including innovation platforms, innovation bundling, multi-actor partnerships, inclusive finance, and multistakeholder dialogues to support farmers' adaptation to climate change.

Keywords

climate change impact, climate-resilient innovation bundle, innovation scaling pathway, mixed food crop-livestock-tree system, northern Ghana

Introduction

Over the last several decades, climate change has profoundly impacted farming systems across sub-

Saharan Africa (SSA). The changes are visible by increased temperatures, droughts, floods, erratic precipitation patterns, increased incidence and types of pests and diseases, and declining soil fertility leading to crop failures and livestock mortality in much of SSA landscapes (Abegunde & Obi, 2022; Akinyi et al., 2021; Malhi et al., 2021; Tui et al., 2021). These climate change impacts (CCIs) and other challenges, such as limited access to markets, capital, technology, extension services, and labor, significantly hinder smallholder farmers from benefiting from farming activities.

Mixed farming systems (MFSs), a complex feature of the agriculture sector, dominate SSA landscapes. Smallholder farmers in SSA manage about 33 million mixed farms (Kim et al., 2021; Lowder et al., 2016) for their livelihoods (Tui et al., 2021). Cereal-based cropping with small ruminants covers about 24% of SSA's land area and provides a livelihood for about 34% of the region's population (Low et al., 2020). Livestock provides draft power, skins, transportation, manure, and protein sources to farmers' incomes and diets. Livestock is also a primary asset that can easily be converted into cash, provides a source of prestige for farmers, and fulfills various sociocultural functions such as dowry payments, religious festivals, and funerals, in addition to a source of emergency cash. Crop residues may be used to feed livestock, while animals provide manure for crop production (Kuyah et al., 2021). Therefore, the livestock component is critical, directly and indirectly contributing to the MFSs' climate change adaptation.

According to Kuivanen et al. (2016), northern Ghana has several farm types based on farm size, household size, hired labor, land use, livestock, and income variables. These are (a) large farms; (b) semi-large farms; (c) medium-size farms; (d) small-size farms and (e) micro-size farms, as summarized in Table 1.

Large farms (over 6.3 hectares or 15.6 acres) have about 50% of the cropped area dedicated mainly to the production of maize. The average livestock per household with a large farm is about 10 cows, 10 goats, and 10 sheep, and non-farm activities contribute to about 32% of incomes. These farms have large households of about 22 people providing most of the on-farm labor. Semi-

Table 1. Farm Types in Northern Ghana

Farm type	Farm size (ha)	Average household size and involvement	Land use	Average household livestock holding	Hired labor	Income variables
Large	Over 6.3	22 people; main source of on-farm labor	50% in maize	10 cows, 10 goats, 10 sheep	Minimal	32% of income from non-farm activities
Semi large	Up to 6.3	Relatively large household; main source of on-farm labor	33% in maize, 33% in legumes	7 cows, 4 goats, 3 sheep	Minimal	More than 50% of farm income from crop sales
Medium	Up to 5.2	Medium household size; on-farm labor provided by household and hired labor	33% in maize, 33% in legumes	0 cow, 9 goats, 9 sheep	About 8%	Mainly from crop sales
Small	Up to 3.5	Small household size; on-farm labor provided by household and hired labor	Mainly maize and legumes	1 cow, 6 goats, 9 sheep, 34 poultry	About 14%	Mainly from crop sales up to 50% Little to no off-farm income
Micro	Up to 2.6	Small household size; on-farm labor provided by household	47% in maize	Mainly poultry	None	About 42% of the farm income from poultry About 25% of household income from off-farm activities

Note: 1 hectare = 2.5 acres.
 Source: Kuivanen et al., 2016.

large farms (with an average of 6.3 hectares or 15.6 acres) have over a third of the area cropped to maize and another third to legumes. These farms rely heavily on selling crops, with more than half of all crops sold. The average livestock per household with a semi-large farm is seven cows, four goats, and three sheep. Farm labor is provided mainly by relatively large households. Medium-sized legume-and-maize-oriented farms have an average area of 5.2 hectares or 12.8 acres. Of that, a third is cropped to maize and another third to legumes. Livestock of the household is dominated by small ruminants, averaging no cattle, nine goats, and nine sheep. About 8% of the farm labor is hired. Small-size, crop-based farms have about 3.5 hectares or 8.6 acres, with the cultivated area dominated by maize and legumes. About 50% of all crops are sold on the market, and farm income comes mainly from crop product sales. Households cultivating these farms have about one cow, six goats, and six sheep. About 14% of labor is hired due to the smaller household size. Small-size maize and leg-

ume farms have almost no income from off-farm activities, and have a low amount of hired labor. Livestock is mainly small ruminants and poultry, consisting of about one cow, six goats, nine sheep, and 34 poultry. Lastly, micro-size farms have an average land size of 2.6 hectares, with about 47% allocated to maize. Livestock is mainly poultry, which provides about 42% of the farm income. About 25% of income comes from off-farm activities. Household sizes are relatively small, and farms hardly use hired labor.

In MFSs, farmers adapt to CCIs at various scales and with different strategies. At the farm level, autonomous adaptation involves farmers changing farming practices, adjusting their farming management, and altering their livelihood activities, such as reallocating resources (Akinyi et al., 2021). Their adaptation varies according to their resources, needs, and capacities (Magesa et al., 2023). Such responses may be technological (e.g., controlling bushfires and managing temperatures, floods, droughts, and strong winds) (Abdul et al., 2022;

Asare-Nuamah & Antwi-Agyei, 2022), behavioral (e.g., changing dietary choices), and managerial (e.g., changing farm management and investment practices) changes. Farmers combine technical, managerial, and business changes relevant to their farming systems based on local knowledge, previous experiences, extension advice, resource availability, and expectations for future changes. These responses may be gendered, with men responding differently from women due to differences in resource access (Wrigley-Asante et al., 2017). Men, for instance, respond mainly using on-farm activities, while women combine both on-farm and off-farm activities. Such responses reflect farmers' adaptation and resilience to CCIs (Antwi-Agyei & Nyantakyi-Frimpong, 2021; Assan et al., 2020).

Various innovation approaches have been applied to support farmers' climate change adaptation (Abegunde & Obi, 2022; International Water Management Institute [IWMI], 2023; Schut et al., 2018). Systemic innovation approaches enhance systems' capacity to respond to changes using dialogue and negotiation, discovery-based activities, stakeholder experimentation, reflection, and joint learning (Edlmann & Grobbelaar, 2021; Maryono et al., 2024). The approaches facilitate more flexible and adaptive processes, resulting in context-specific innovations that meet farmers' needs. Climate change adaptation is a part of development and vulnerability reduction interventions that foster farmers' ability to act toward CCIs. Technology-centric approaches focus on technology dissemination to increase agricultural productivity using training, demonstrations, and technology transfer (Abdul et al., 2022; Acheampong et al., 2017). These approaches emphasize the importance of transferring improved inputs, mechanical technologies, good agricultural practices, and advanced crop-livestock production techniques. Farmers in SSA have adopted suitable interventions to support their adaptation to CCIs. However, many other interventions must be tailored to increase their relevance to local contexts and farmers' heterogeneity. Farmers are often perceived as passive actors with predetermined intervention outputs and deliverables, limiting these interventions' support for farmers' adaptation to CCIs.

Climate change impacts, challenges, and adap-

tation strategies are well documented (e.g., Akinyi et al., 2021; Assan et al., 2020; Gbodji et al., 2023; Minh et al., 2020; Sherman et al., 2016). However, farmers' adaptation is a complex and dynamic decision-making process (Akinyi et al., 2021; Wiréhn et al., 2020; Zhao et al., 2018), involving characteristics and transitions of farming practices under changing climatic circumstances, socioeconomic conditions, and rural livelihoods. There is a need to understand how interconnections among MFSs' components and CCIs on different aspects of farming systems influence farmers' adaptation (Thornton & Herrero, 2015). Integrating innovation perspectives into MFSs and farmers' adaptation is needed to analyze synergies among systems' components, farmers' changes in farming practices, and their innovation needs. Furthermore, insights into innovations that farmers need in mixed farming systems in SSA are still fragmented, although innovation adoption is highlighted as essential to support farmers' adaptation (e.g., Adjei et al., 2020; Akrong et al., 2023; Schut et al., 2018). Systemic innovation approaches have shown a foundation to support climate change adaptation. The remaining question is how we operationalize the systemic approaches to scale innovations to facilitate farmers' responses to CCIs, while minimizing tradeoffs and improving synergies in the SSA's MFS contexts (Akinyi et al., 2021; Boon et al., 2021).

To address these gaps, we analyzed farmers' adaptation to climate changes in SSA's MFS contexts. Specifically, we investigated how farmers respond to CCIs, what innovations farmers need to respond to the impacts, and how the innovations can be catalyzed to enable farmers' adaptation.

This article presents a qualitative analysis of the mixed crop-livestock-tree (MCLT) systems in northern Ghana, contributing to various aspects of climate change adaptation literature. Farmers have diverse responses to CCIs in their farming systems. Technical changes combining local and improved agronomic practices are dominant. Managerial and business changes in cropping season, livestock, investment focus, farming de-intensification, and reduction in commercial scale are limited, indicating farmers' modest responsiveness and adaptation to CCIs. Climate-resilient innovation bundles that farmers need for their adaptation include circular

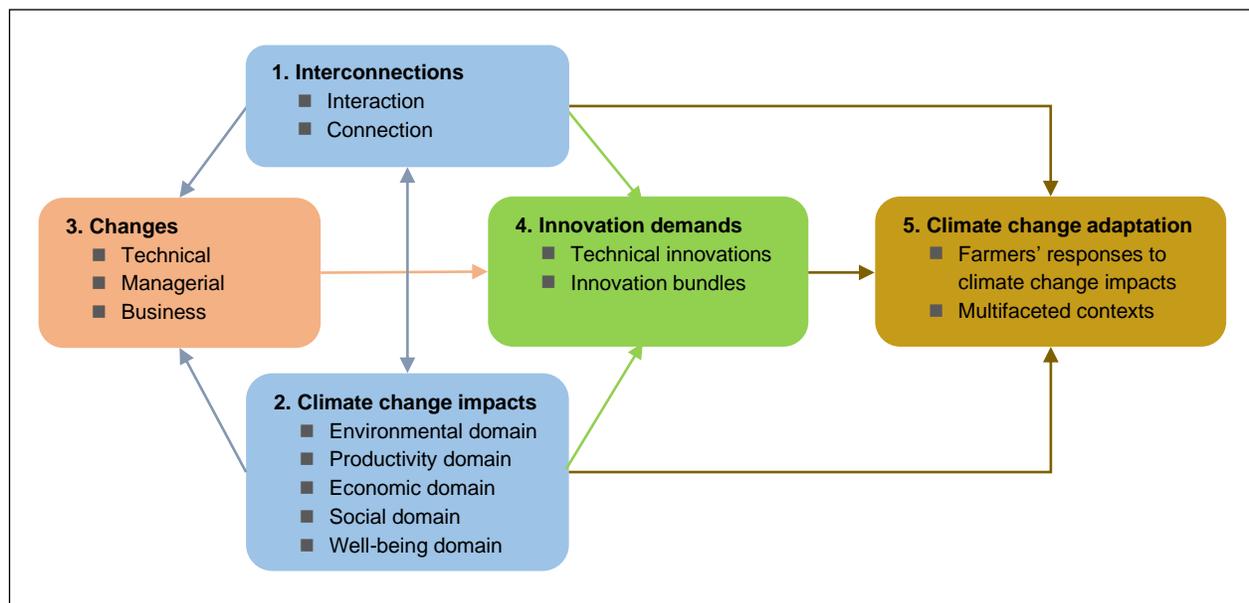
farming techniques, information services, irrigated farming, and value-chain linkages. These bundles are characterized by suitability to farmers' MFS needs, inclusivity to diverse farmers' capacities and available resources, and adaptability to dynamic changes in multifaceted contexts. These highlight a need for multiple pathways for scaling climate-resilient innovations in MFSs, especially in SSA.

Analytical Framework

Scholars define mixed farming systems (MFSs) from a broad or narrow perspective. The narrow perspective views MFSs as farmers combining cropping with livestock cultivation and drawing interactions and synergies from these activities (e.g., Liang et al., 2018; Thornton & Herrero, 2015). The broad perspective views MFSs as diversified agriculture, such as rainfed and flooded cereals, groundnuts, cotton cash crops, and extensive livestock raising (Manlay et al., 2004), and interactions between crop and livestock subsystems and the underlying agroecological and socio-economic conditions (Parthasarathy & BIRTHAL, 2008). Aligning with the broad perspective, we define MFSs as "systems where multiple components of livestock, trees, subsistence crops, cash crops, and horticultural crops exist and interact on the same farm or

landscape, offering opportunities to capitalize on synergies" (Hoeschle-Zeledon & López Ridaury, 2021, p. 3). To analyze farmers' climate change adaptation under the climate change-affected MFSs, we used a holistic framework to analyze the MFSs at the farm level, capturing five interconnected analytical elements (Figure 1). First, interconnections are interactions between the MFSs' core and complementary components and connections between the component's outcomes. The core component include main MFS activities that generate primary income sources and household food security. Complementary components include other farming activities that provide farmers with secondary incomes and cash flows (Ahiagbe et al., 2021; Danso-Abeam et al., 2021). For example, in cereal-based cropping systems, maize, sorghum, and millet are the core components, complemented by roots and tubers (e.g., cassava, yam, and potatoes), legumes (e.g., pigeon peas, cowpeas, beans, soya beans, and groundnuts), and livestock (e.g., goats, sheep, and cattle) (Kuyah et al., 2021). In tree-based systems, cash crops like cashews and mango serve as the core component, and food crops are complementary (Danso-Abeam et al., 2023). These interactions and connections enhance farming and economic resilience, such as through

Figure 1. Analytical Framework for Unpacking Farmer Innovation Demands for Climate Change Adaptation in Mixed Farming Systems



the reuse of animal droppings, soil health improvement, control of pests, diseases, weeds, and temperature, as well as using cropping income to support livestock production and vice versa, and livelihood improvements such as income risk management and nutrition improvement (Danso-Abbeam et al., 2021).

Second, *climate change impacts* have multiple aspects (Musumba et al., 2017). The environmental aspect examines pest levels that may influence agricultural productivity, water resources, availability, and sufficiency for crop irrigation and household consumption. The productivity reflects crop productivity (in kg/ha/season), measuring annual plant production per unit area per unit time or net primary productivity. Yield refers to the output for a given land area in a season. Crop biomass productivity is forage production per kg/ha/season, which assesses the land unit's productivity in terms of all produced, not just the grain yield. The economic aspect includes income diversification, which measures the household's income generation from multiple sources and food security during production or weather risk. Furthermore, labor requirements consist of hours, cost, and the seasonal supply and demand needed for farming production. Market participation examines where farmers sell agricultural commodities and buy inputs. Market orientation investigates the household's MFS production destined for the market (Musumba et al., 2017). The social aspect scans gender equity at the field, farm, and household levels by assessing differential ownership and access to resources for agriculture, control over resources (agency), time management, and sources/control/use of incomes. The well-being aspect includes household nutrition and food (in)security, such as availability and accessibility. Food accessibility requires adequate quantity and quality to meet household members' nutritional requirements. Food availability reflects enough quality food supplied through domestic production or importation for a productive life.

Third, changes in MFSs due to CCIs refer to what farmers do differently at the farm level in response to CCIs. For example, technical changes are new or adjusted agronomic practices applied to farming. Managerial changes reflect how farmers

manage the whole mixed farming system when it or its specific component is affected by climate change. Business changes are different ways farmers do farm business, focusing on markets and private investments. Fourth, *innovations* farmers need to respond to CCIs are in the form of technical innovations or bundles of contextually relevant products, services, and business management farmers require to adapt their farming systems to CCIs (IWMI, 2021; Minh et al., 2024; Ofosu & Minh, 2022a).

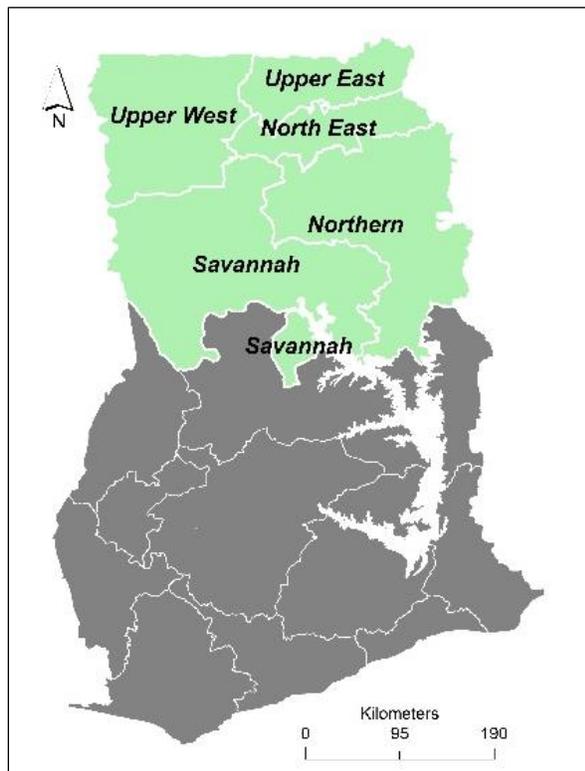
Fifth, Climate Change Adaptation is a process of adjusting to the actual or expected climate and its effects to minimize the trade-offs and optimize the synergies (Akinyi et al., 2021). Such adaptation is essential for households and communities to secure their livelihoods and build resilience to CCIs. Akinyi et al. (2021) categorized farmers' climate change adaptation into five broad strategies: crop, risk, soil/land, water, and livestock management. In this study, climate change adaptation refers to farmers' responses to CCIs embedded in the complex MFS context, multiple impacts, and dynamic enabling environment factors such as innovations, value-chain linkages, socio-economic barriers, and opportunities. Such multifaceted contexts shape farmers' needs to make technical, managerial, and business changes to deal with the risks and shocks posed by climate change.

Methodology

Study Areas and Case

This study focused on northern Ghana's (NG) mixed crop-livestock-tree (MCLT) systems to analyze changes, emerging trends, and innovations needed to enable smallholders to cope with CCIs. The study areas encompass the Northern Region (NR), Northeast Region (NER), Savannah Region (SR), Upper East Region (UER), and Upper West Region (UWR) (Figure 2). It is a central agricultural hub in Ghana for crops and livestock and a source of employment for about 95% of the population. Northern Ghana is vulnerable to climate change impacts due to high temperatures, the single rainfall season, and high poverty levels (Klutse et al., 2020).

Figure 2. Study Area in Northern Ghana



Map credit: Komlavi Akpoti, IWMI.

The NG MCLT system was chosen for this study because it is the primary farming system in the zone, is heavily affected by climate change, and provides livelihoods for many households. In these systems, the crop component is dominated by rain-fed maize and irrigated vegetables for home consumption and local and export markets (Cudjoe et al., 2021; Rahman et al., 2019). They employ local and modern methods of pest management and post-harvest management (Acheampong et al., 2017; Amedor et al., 2020; Asare-Nuamah, 2020). The dominant livestock are West African dwarf goat and sheep breeds, kept mainly in free-range systems (Abdul et al., 2022). Common trees include shea and *dawadawa* (*Parkia biglobosa*), which grow naturally in the environment, and cashews and mango, which farmers grow as cash crops.

Primary Data and Analysis

Primary data were collected from 2020 to 2024 using semi-structured interviews, focus group discussions, and stakeholder workshops with farmers

and other value-chain actors. We conducted 46 semi-structured interviews, 29 focus group discussions, and 11 stakeholder workshops. Semi-structured interviews and focus group discussions covered broad topics. These topics include different components and their interconnections and farming techniques in the MCLT system, including crop and tree cultivation, livestock raising, irrigation practices, on-farm and off-farm alternative income-generating activities, climate and weather condition impacts on farmers' farming and livelihood practices, changes in farming practices, investment, and livelihood strategies, and individual and farmer group preferences for innovations to assist with the changes. Stakeholder workshops reflected on the impacts, changes, and innovation preferences identified through the semi-structured interviews and focus group discussions and consulted participants on practical ways for them to access innovations. Initial respondents for semi-structured interviews, focus group discussions, and stakeholder workshops were identified with the help of Ghana's Ministry of Food and Agriculture extension agents. The snowball technique was then used to identify other respondents across the five regions. The UER, UWR, NER, SR, and NR respondents were involved in investigating farming practices, irrigation system investments and applications, market linkages, and value-chain dynamics. In 2024, we conducted additional semi-structured interviews and focus group discussions in SR to understand the tree component in MCLT systems better. Data was collected in local languages and then transcribed and translated into English for analysis.

We assigned labels to quotes from the primary data to describe the respondents as follows. "Aggregator" refers to middlemen who buy food crops, shea nuts, and cashews from farmers for bulk sale to other markets or companies. "Male farmer group" refers to a formal or informal group of male farmers. "Female farmer group" refers to a formal or informal group of women farmers. "Young male/female farmer" refers to men or women farmers up to 35 years old. "Middle-aged male/female farmer" refers to men or women farmers between 36 and 50 years old. "Old male/female farmers" are men or women farmers over 50 years old. "Gender researcher" refers to a male

or female person who carries out academic or scientific research with a focus on issues relating to women and/or men.

We employed qualitative content analysis (Elo & Kyngäs, 2008), following preparation, organization, and presentation phases for a rigorous, category-led, inductive, primary data analysis. In the preparation phase, we reviewed each transcript several times to familiarize ourselves with it. Our reading was guided by questions such as who tells what happens, where, when, and why to immerse in the data and obtain a general understanding of NG MCLT systems. Based on the understanding and analytical category-led scheme presented in Figure 1, all transcripts were read through again to identify texts with contents related to the analytical dimensions (e.g., interconnection, climate change impacts, changes, and innovation demands) and arrange them according to each category under the corresponding dimension (e.g., interaction and connection under the “interconnection” dimension). We also started organizing the identified texts into categories, enabling us to recognize and recontextualize the data to give a fresh perception of visible themes.

We then developed a tentative, more extensive set of subthemes (or codes) to identify reoccurring themes that were later used to form subcategories under each category. The most frequent words and short phrases in the categorized texts that contributed most to describing and interpreting the meaning of themes were entered into the coding. Guided by the identified subthemes, we reread the data excerpts to search and refine the reoccurring themes. We organized them into themes under categories corresponding to the analytical dimension inductively. We analyzed the organized themes to reflect relationships, make arguments, and present them together in coherent stories that answered the research questions. During this process, we reflected on the relevance of subthemes and reoccurring themes to research questions. We also compared the categorized data with other observations from other themes to increase the understanding of connections between and among subthemes and categories, providing a means of describing the climate change adaptation phenomenon under each dimension. Figure 3

presents an overview of the coding scheme and process.

Results

We present the results of our study, focusing on the interconnections among MFS, climate change impacts, farmer changes under changing climate conditions, and climate-resilient innovations required to support smallholder farmers.

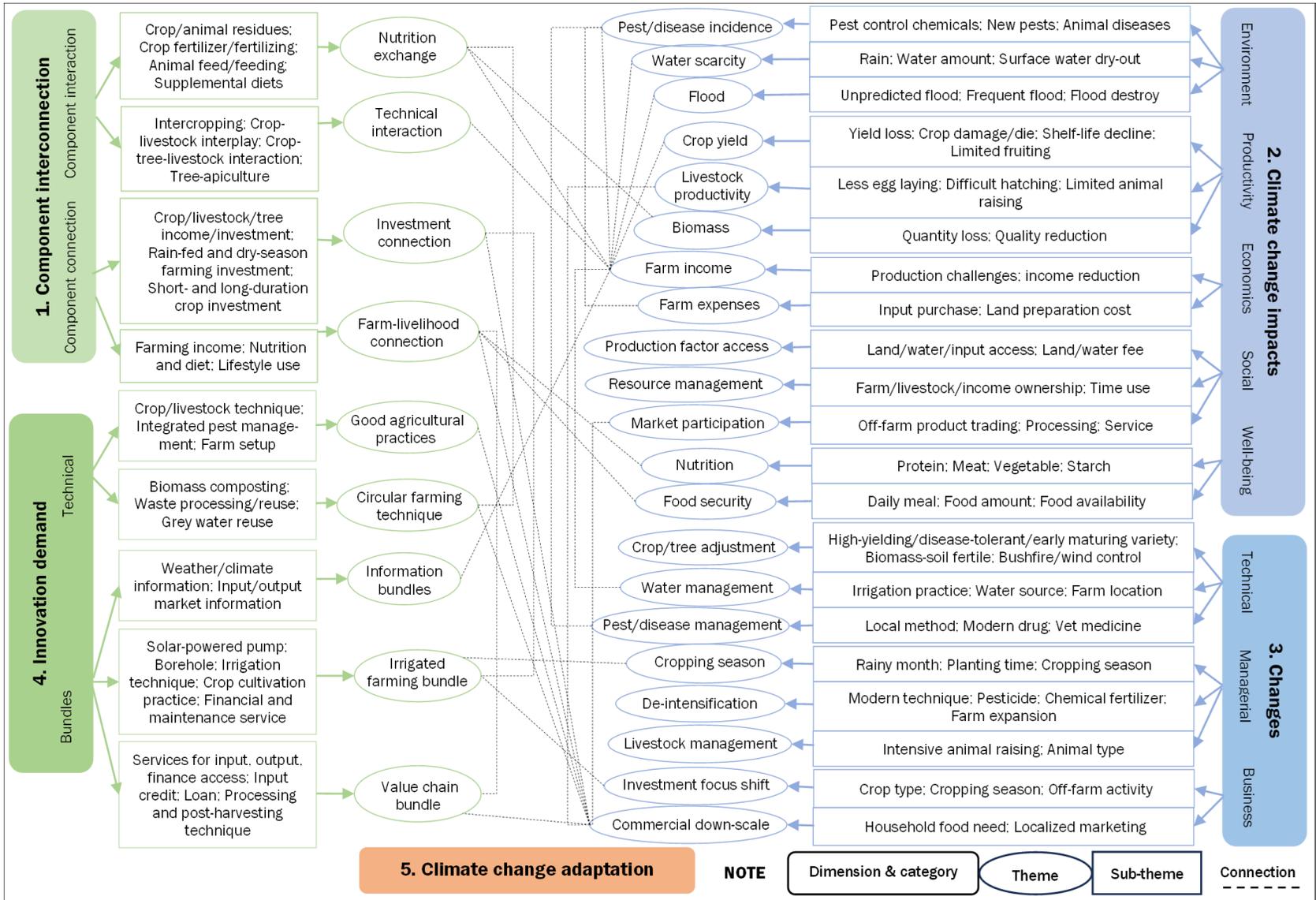
Interconnections in Mixed Crop-Livestock-Tree Systems

Analyses show various interconnections among MCLT systems' components. Cross-component nutrient exchanges are found when farmers use byproducts from one component as inputs for other components. For example, farmers apply poultry, cattle, and small ruminant manure to improve soil quality. They use crop residues to complement livestock feeding, soil fertilizing, and fuel sources. Crop residues and tree crops feed animals as supplementary diets during the dry season: “I feed guinea fowls and chickens with millet and maize. I feed them with termites trapped with cow dung from my farm” (Old male farmer, Bonia, UER). However, using crop residue is minimal due to multiple challenges, as expressed by farmers: “We do not get crop residues from our farms because the Fulani cattle are always around to eat the residues. The cattle sometimes consume even parts of the harvest” (Mixed farmer group, Chancheri, SR). An agriculture department staff member in Savelugu, NR, also indicated,

Storing crop residues for livestock feed is always challenging, except for the late peanut harvest when there is less rain. Livestock do not feed much on rice straw because farmers do not know how to prepare it. Wild bushfires also burn crop residues as farmers focus more on securing their harvest.

Technical integration occurs when farmers manage all components as a single unit to optimize benefits while addressing tradeoffs. Farmers cultivate crops and raise animals to benefit from improved soil fertility and healthy crops and animals. Farmers grow vegetables on the loamy part

Figure 3. Overview of Data Analysis, Capturing Subthemes and Themes Identified from the Data, their Corresponding Categories and Dimensions Presented in the Analytical Framework, and Connections among Themes across the Dimensions



of their farm and rice on the clayey portion, which is prone to floods, while using rice residue for feeding their poultry: “Vegetables cover about two acres, and the rice covers another two acres. I feed chickens and guinea fowls with rice residue” (Old male farmer, Bonia, UER). Farmers also maximize benefits from connecting different farming activities. Some cashew farmers indicated higher yields on trees that contain beehives due to improved pollination: “I have noticed that the trees fruit better after hanging the hives on them. The bees take nectar from the tree but also offer some benefits” (Young female farmer, Canteen, SR). Raising bullocks and donkeys helps crop cultivation by aiding with preparing the land, transporting inputs, and bringing farm produce to the markets.

Investment connections are found when incomes from one component are used to invest in others. Farmers use incomes from rain-fed and tree crops to purchase inputs for dry-season cultivation, and vice versa. Farmers sell short-duration crops to buy the essential inputs such as fertilizer and pesticides needed to re-invest in more profitable long-term core crops. They also purchase livestock with income from rain-fed and dry-season cultivation and tree crop outputs: “During the dry season harvest, we use money from the sale of shea nuts and butter to buy ruminants and other animals” (Farmer groups, Gingani, NR, and Akuriyi, SR).

Finally, farming-livelihood connections occur when different components of MCLT systems support family nutrition, social, and health needs. For example, hunting for game and wild birds complements farmers’ diets and incomes: “We hunt rabbits, grasscutters, rats, and monkeys, and collect wild honey” (Mixed farmer group, Akuriyi, SR). The tree component supports families in several ways besides providing income:

Shea butter is a body lotion, and the shea residue is used to ignite fires when cooking. The shea branches and trees serve as firewood. The shea and dawadawa trees have medicinal properties. The baobab leaves are used for soup, and the fruit is eaten or used to make yogurt.” (Gender researcher, Tamale, NR)

Climate Change Impacts on Mixed Crops-Livestock-Tree Systems

We found visible climate change impacts across five sustainability domains. However, these impacts are more visible in some domains than others, as some are more impacted. In the environmental domain, climate change increases pest and disease incidence, water scarcity, and floods. Farmers observe new crop pests and diseases, but they have no experience to assist with management:

Any chemical we try to control grasshoppers, maggots, and snails does not work. Snails are new to us, and we do not know how to handle them. Snails will leave our crops alone if they eat enough of the maize. Sometimes, we do not feel like going to our farms again. (Farmer groups, Akuriyi, SR)

Farmers also observe more extreme water scarcity and its consequences: “We cut down all the big trees for charcoal, so now the rains do not come as expected. When there is no rain, many cattle come here to drink water, reducing the water amount for our cashew nursery” (Farmer groups, Akuriyi & Seripe, SR). “Around April or May, most of these dugouts get dried up. Only a few near the dam still have water to produce a few vegetables. Those who cultivate in large areas run out of water” (Male farmer group, Kaleo, UER). Floods occur unpredictably, causing farmers near surface water bodies to restart farming activities on other lands or limit cultivation to only one season: “I only farm during the dry season because the flood destroys the crops during the rainy season” (Young male farmer, Bole, SR). Floods sometimes lead to total crop loss: “The floods happen yearly, and parts of our farm get flooded. Last year, the water washed every crop on the farm” (Mixed farmer group, Daboya, SR).

Consequently, these environmental impacts influence farm productivity. Rain, temperature variability, and soil fertility affect crop and livestock productivity: “It has been hotter in recent years than before. The heat makes our crops wilt. Yams and okra die from excessive heat; cashews are not fruiting well. The chickens find it difficult to lay eggs or hatch them” (Farmer groups in Chancheri, Seripe, and Bole, SR). Vegetable shelf-life declines,

as observed by a farmer in Saboro, UER: “In the dry season, we cultivate perishable vegetables. At harvesting, vegetables are exposed to high temperatures, reducing their shelf life.” Soil fertility, crop yields, and residues are declining due to hungry cattle damaging crops while looking for food, and unintended fires in the dry season:

About five years ago, I harvested about three to four 160 kg bags per acre by adding fertilizers. Now, I am even lucky to get a basin of maize, which is about ¼ of a bag. Wild bushfires burn most crop residues because we do not create fire belts around our farms. (Mixed farmer group, Akuriyi, SR)

In the economic domain, climate change reduces farmers’ farm incomes while increasing farm expenses due to increasing activities to manage pests and diseases, high temperatures, floods, droughts, bushfires, and cattle invasions. This limits their ability to reinvest in farming activities. Describing the main challenges of vegetable farming, a middle-aged male farmer in Bole, SR, indicated, “We have many challenges, starting from buying the seed to selling products and getting money from the market. We face unfavorable weather conditions, cattle invasion, no water, and plant disease.” Due to high temperatures, the increased perishability of vegetables pushes some farmers to sell on credit, locking up their business capital: “The sun is hot now and then, destroying plants. Vegetable traders buy and sell peppers and make their profits. However, they will not bring your money unless you remind them. This is a big challenge for us” (Young male farmer, Gia, UER). “When water was enough to grow crops, we harvested more, sometimes up to 300 Ghana Cedis [~US\$21]. However, due to water scarcity, we can only make about 40 Cedis [~US\$3]” (Female farmer group, Seripe, SR). Cattle searching for water and pasture invade farmers’ farms, making the soil compact and increasing their cost of land preparation: “The cattle walking on the field makes the soil hard. It is costly to use a tractor to till such hard soil. A tractor charges 300 Cedis [~US\$20] per acre. Now I pay 350 Cedis [~US\$24] for hard soil” (Farmer group, Chancheri, SR).

In the social domain, climate change affects women’s access to production factors, resource management, and market participation. Women access land through joint cultivation with husbands and sons, community generosity, rental, or labor-for-land arrangements: “One acre of land is for my father, but the other three acres are rented. I pay 50 Cedis [~US\$4] per acre each season” (Middle-aged female farmer, Tinguri, NER). Land contentions favor men, as expressed by a middle-aged woman in Tatale, SR: “We were the first to cultivate this land, but last year, we did not even get a place to farm because men claim the land is not for us.” Women cannot optimize crop cultivation due to limited access to inputs: “Women have difficulty accessing inputs, costly fertilizers. They find it difficult to intensify cultivation even on the small land they can access” (Gender researcher, Tamale, NR). Women’s water access is also affected. Women pay to use the community borehole even for domestic purposes, while the men use the water for irrigation for free: “We do not pay for the water. Women pay. We use the money we take from the women to pay for electricity to operate the pump. This is because when the pump breaks down, the men fix it” (Young male farmer, Daboya, SR). Some also abandon their farms due to water shortage: “Sometimes there is no water for three months, starting in March. Our group had 60 women, but some left because of difficulty carrying water in basins for irrigating crops” (Female farmer group, Bole, SR; Young male farmer, Wovogma, NR).

The above-mentioned environmental impacts affect women’s resource management. Farmland loss increases for women while they spend more time farming. Some youth frustrated with challenges in agriculture migrate to southern Ghana or other communities as farmhands or illegal gold miners. This results in labor shortages that impact women’s use of time: “It is difficult to get hired labor, so women spend more time on farms. Women fetch water early in the mornings and prepare food late in the evenings” (Mixed farmer group, Seripe, SR). Furthermore, increases in pests and diseases reduce women’s livestock ownership and incomes from both livestock sales and farm crops: “Our fowls and other animals died this year.

Only the vaccinated ones survived” (Female farmer group, Bodia, SR). Women’s involvement in decision-making is limited due to socio-cultural norms and limited access to land, water, and other resources. This relates to agricultural production and earnings decisions, membership in agricultural associations, and on-farm and off-farm activities:

Woman gives to her husband to buy her poultry when she has money. She cannot decide whether to buy or dispose of poultry. She can only suggest that her husband sell one bird to meet a need. He negotiates the price and gives his wife some or all the money because the poultry was raised in his compound. (Gender researcher, Tamale, NR)

Women’s market participation in input markets shifts toward trading on-farm and off-farm products. As limited land, water access, and yields decline, women shift to trading food items, local alcohol (*pito*), repackaged fertilizer and cement, and offering services such as rice threshing and drying or harvesting crops: “The women are more involved in the marketing of farm produce because they are not strong enough to draw the water. There have been instances of people falling into the water” (Male farmer group, Kaleo, UWR). They also reduce the quantity of their purchase of farm inputs such as seeds, fertilizers, herbicides, and pesticides to a smaller scale.

Human nutrition and food security are the most impacted indicators in the well-being domain. Farmers take one to three meals daily, with family sizes of five to 25 members. Carbohydrates dominate the family meal, complemented by local leafy vegetable soups with limited protein intake due to income constraints. Respondents indicated that they prefer to consume three to four meals daily and enrich them with proteins: “If we have more money from our farm, we want to eat three times daily instead of two. We will add fish, meat, chicken, and guinea fowl to vary our meals. April to July is the most difficult time when we exhaust food stock, and planting crops has just begun. We buy food from the market, reduce the food amount, and warm leftovers for the family during

these months” (Mixed farmers group, Akuriyi, SR).

Changes Under the Changing Climate Conditions

Our data analyses showed several technical, managerial, and business changes by which farmers respond to climate change impacts. Technical changes were found in adjusting techniques to manage crops and trees. Farmers start using high-yielding, disease-resistant, and early maturing crop varieties at a limited scale as, “New seeds are expensive and are unavailable even for those who have the money to buy” (Gender researcher, Tamale, NR). They control bushfires by creating fire belts and maintaining farm sanitation: “Bushfires disturb cashews a lot. I avoid them by weeding around the trees at least twice yearly” (Male farmer, Damongo, SR). They grow trees at farm edges to manage strong winds and integrate crop residues and tree leaves into the soil where they are available to improve fertility. They combine traditional and modern pest and disease control methods in crops and livestock: “We control stem borers by sealing holes with sticks or spraying them with pesticides and weevils using ash or a mixture of powdered pepper and finely sieved sand” (Farmer groups, Akuriyi and Seripe, SR).

Farmers change irrigation practices to save water: “Water is not enough in my borehole. So, I work with drip to manage the water better” (Young male farmer, Saboro, UER). Others combine drip and sprinkler irrigation and use irrigation to wash off small insects without wasting water: “Drip economizes the water, but I also use water to control pests and diseases in the dry season. It also saves agrochemicals” (Stakeholder workshop participant, Bolgatanga, UER). Others explore groundwater by sinking multiple boreholes or dugouts and farming with residual water: “I sunk this borehole because of low water yield” (Young male farmer, Gambibgo, UER). “Women dig dugouts in waterlogged areas to collect water for irrigation” (Mixed farmer group, Balawa, UER). Surface and groundwater use changes local communities’ rules to manage water scarcity in the dry season: “We can only use buckets to irrigate in the dry season. If motor pumps are allowed, some people will draw more, and water will run out quickly” (Mixed

farmer group, Baakye, UWR). Farmers have also changed the location to farm during the dry season: “We grow crops within the riverbed as the water declines. When the dam dries, the soil still has moisture enough for crops” (Male farmer group, Daboya, SR). Some abandoned their plots, reduced cultivation, and used grey water: “From March, the water has gone, so we reduced the size of our gardens. I use any water in my field, even if it is unclean” (Mixed farmer group, Bole, SR; Young farmer, Saboro, UER).

Managerial changes due to limited capital and CCIs include cropping calendars, low farm intensification, and livestock adjustments. Farmers shift cropping calendars in response to erratic rainfall patterns: “We change planting time to wait for rains to come. June used to be the rainy month. Now, rain has not come, maybe because of excessive logging, especially the mahogany and rosewood, and cutting trees for charcoal” (Farmer groups, Akuriyi & Seripe, SR). Crop de-intensification to reduce farming investments and risks was observed across study areas with decreasing use of expensive, modern techniques: “We spray pesticides on only parts of the farm due to lack of money” (Mixed farmer group, Chancheri, SR). Elderly farmers expand their farms continuously for prestige despite their limited ability to manage large farms: “We are getting older and weaker. We need to concentrate on farm size. However, some still expand their cultivation as they have much land they want to farm before stopping” (Mixed farmer group, Damongo, SR). Changes are also visible in adjusting livestock components: “We do not rear pigs anymore because they have swine fever, which wiped out the pigs, and it recurs. Keeping our goats, sheep, and poultry intensively is better than losing them to disease” (Mixed farmer group, Damongo, SR).

Business changes are found with shifting investment focus and commercial scale. Investment changes occur with farmers shifting cultivated crops, cropping seasons, and non-farm activities. Some farmers shift from long- to short-duration crops, such as vegetables, to harvest before the severe water and pasture scarcity periods that attract herders to allow their animals to graze at their farms. Replacing vegetables with

longer maturing crops, like cereals and tubers, increases harvests to avoid glut and high perishability. Some farmers farm only one season to respond to water scarcity: “In the dry season, I do not cultivate because there is no water” (Old male farmer, Bonia, UER). This is typical among “mobile” farmers who move from their communities to rent land close to water bodies to cultivate: “We mostly rent land close to water sources to farm during the dry season” (Male farmer group, Bamboi, SR). Others focus on cultivating dry-season vegetables to take advantage of high prices:

Vegetable prices are vastly different between wet and dry seasons. In the rainy season, vegetables are available and cheap compared to the dry season, when water is scarce. A bag of peppers that sells for 800 Cedis in the dry season [US\$55] will sell for 300 Cedis [US\$21] in the wet season. (Farmer groups, Baakye and Jambosi, UWR)

Farmers often invest in wet and dry seasons to compensate for harvest losses in one season: “Sometimes the wet season can fail. Harvest levels are not adequate. We fall on the dry season farming to compensate for the loss” (Mixed farmer group, Gingani, NR). Farmers abandon crop components and invest more in off-farm activities in regions with extreme drought and weather conditions like SR: “Yield has reduced because challenging weather and cattle destroy our crops. We sometimes lose 2 to 3 acres. Some people have stopped farming and ventured into charcoal production and trading” (Mixed farmer group, Chancheri, SR).

Finally, reduction in commercial scale is visible when farmers balance household food consumption needs and earning income for other livelihood activities: “As our harvest is reduced, we decrease products selling to markets. When we have 20 bags of maize, we keep six at home. For cassava, we keep four out of 20 for food. We sell maize to aggregators and cassava to gari [roasted cassava flakes] processors in the village or buyers in the Bono East Region” (Mixed farmer group, Damongo, SR). Other farmers cultivate with the intention of selling but cannot do so: “We grow food crops to sell some, but because of low yields,

we end up eating them all” (Mixed farmer group, Bodia, SR). Farmers sell more of their produce within the communities due to food shortages among farming families: “This year, it is difficult for families to come by foodstuffs. We used to send maize to the market, but now, people here buy because of the food shortage” (Mixed farmer group, Akuriyi, SR).

Climate-Resilient Innovations to Support Smallholder Livelihoods in Northern Ghana

We clustered farmers’ needs for climate-resilient innovations in their MCLT system into two categories, as presented in Figure 3. Technical innovations include good agricultural practices related to all aspects of farming, such as farm setup and organization, crop and animal production techniques, and integrated pest management. These practices help farmers increase the productivity of crops, livestock, and trees, making them more resilient to climate change impacts. Some farmers indicated their GAP needs:

We must plant at the correct time, apply fertilizers, pesticides and herbicides, and prune. We must keep animals in clean pens and bathe them. We want to know how to supplement feed and clean water for animals and invite veterinarians to check them occasionally.” (Mixed farmer group, Damongo, SR)

Farmers also need circular farming techniques such as crop residue composting and storage and farm waste and/or water recycling to enhance soil, crop, and animal health, reduce chemical inputs, and reinforce biodiversity, as an old farmer in Bole, SR, indicated: “I have a cashew farm with yam, a fishpond, and a vegetable garden. When I change the water from the fishpond, I use it to irrigate the garden.”

Innovation bundles include information, irrigated farming, and value-chain bundles. Information bundles encompass weather and climate and input and output market information that supports farmers in making farming-related decisions: “Rain pattern and frequency have changed over years. We could initially predict when the rain would come and farm, but now, it is unpredictable.

We need more reliable weather information” (Cashew aggregator, Damongo, SR). Digital weather forecasts and radio and television help improve farmers’ access to weather and climate information. In addition, farmers need extension services to provide crop and livestock production information: “The number of times the extension officers visit us depends on our relationship with them. Hence, our older women advise us on what to do because they have been farming for years. Our brother also comes around” (Middle-aged female farmer, Daboya, SR; Female farmer group, Bihee, UWR).

Irrigated farming bundles include water-source development (e.g., borehole development and mechanization), water lifting, storage and application (e.g., motor and solar pumps, drip systems, sprinklers, rain tubes, and storage tanks), irrigation practices, agronomy techniques, and financial services. Bundles of solar-powered irrigation pumps and pay-as-you-go (PAYGO) or pay-as-you-own (PAYOWN) financing models are suitable for investing in irrigated farming, as farmers can better access surface and groundwater and accessible solar energy sources. The bundles are in high demand for farmers to improve access to water for dry season farming:

Solar-powered pumps can fit our farming conditions. We can pay the upfront cost of the pump. We can also pay part of the amount and commit to paying the rest. We have a payment agreement based on how much we can pay regularly. We can spread the cost according to our harvest cycle or monthly. Finally, we can have pay-as-you-go or pay for the water we use. (Middle-aged male farmer, Gia, UER)

Value-chain bundles encompass services that help farmers access input and output markets, finance and credit, processing techniques for value addition and post-harvesting, and farm business and investment management. The bundles strengthen access to climate-resilient vegetable seeds, mechanization, storage, processing, markets, market linkages, information, goods, and services flow along the MCLT value chain. Accessible and affordable inputs such as

seeds, planting materials, and chemicals are needed:

We need fertilizers and other inputs which we buy from the agricultural office or agro-chemical shops about 5 km or more away. Sometimes, these inputs can be found only in Bole, about 10 km from here. Some of us travel to Techiman, which is over 100 km, to buy inputs.” (Farmer groups, Akuriyi, Bodia, and Seripe, SR)

As many farmers and aggregators indicated, financial services include extended- to medium-term loans and input credit:

Farmers need fertilizers, herbicides, and money to hire labor and buy inputs. We [aggregators] supply these inputs to farmers as a form of credit. This helps recover our investments in two or three repayments. We also have agreements with farmers to sell us their produce.” (Cashew and shea aggregator, Akuriyi, SR)

Demands for processing techniques and post-harvest handling for value addition are visible: “We need inputs for vegetables and processing techniques to produce drinks, jam, and candy from cashew apples. We also make shea butter, Dawa Dawa-fruit food condiment, and roasted cassava flakes” (Farmer groups, Damongo and Akuriyi, SR).

Discussion

Climate Change Impacts and Farmers’ Responses to the Mixed Farming Systems

This analysis shows a significant decline in crop yield, livestock productivity, and productivity of the NG MCLT due to multiple CCIs. This is visible in the declining quantity and quality of food and cash crops, biomass, trees growing naturally in the landscape, and livestock. Abdul et al. (2022) also indicated that regional maize yield is about 1.6 tons/ha out of a potential of 5.5 tons/ha, mainly due to erratic rainfall patterns and reported declining livestock productivity as a result of dry season water shortages and high animal mortality.

MCLT systems’ productivity decline results in a reduction in farmers’ incomes and household food security. This is reflected in less diverse diets and declining household food quality and quantity. Our study shows that households consume up to two maize-based or millet-based meals daily, despite a high preference for various foods and three to four daily meals. Acheampong et al. (2017) indicated that climatic conditions in NG do not permit some households to produce diverse crops, contributing to food insecurity among over 20% of farming families in the region. Households are food secure when they have continuous physical, social, and economic access to “sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life” (World Food Summit, 1996, cited in FAO, 2022, p. vii). Danso-Abbeam et al. (2023) indicate that average households in NG consume about eight food groups weekly, and farmers with large landholdings are less food-insecure. However, our study shows that large landholding farmers are not necessarily more productive due to their inability to purchase adequate inputs and the limited application of good agricultural practices due to low labor availability.

Interconnections between components in the NG MCLT systems help generate income and cash flow while improving food and nutritional security. For example, farmers use incomes from rainfed crop cultivation to invest in livestock raising, and incomes from livestock sales to invest in dry-season farming. Farmers improve animal feeding and healthcare and enhance soil quality using crop residues as fodder and mulch (Ahiagbe et al., 2021; Akrong et al., 2023). Such cross-component nutrition exchange and investment connections support additional income generation and improved family nutrition, as confirmed by other authors (e.g., Assan et al., 2020; Danso-Abbeam et al., 2021). Access to nutritious foods and a higher income strengthens farmers’ ability to adapt to CCIs. This enables them to diversify their farming activities and provide financial capital to engage in new on-farm and off-farm activities or expand existing businesses.

Our findings identify diverse managerial and business changes farmers made in responding to

CCIs. Most farmers focus on technical changes, such as planting, pests, crop diseases, bushfire control, and animal breeding, feeding, and healthcare (Asare-Nuamah, 2020; Wrigley-Asante et al., 2017). These technical changes may lower farm risks more quickly than managerial and business changes. Technical changes often combine indigenous and modern methods, depending on farmers' information access and perceptions of climate change severity and threat (Malhi et al., 2021). Changes in planting timing, livestock management, and investment focus are examples of farmers' short-term actions toward CCIs, reflecting farmers' limited responsiveness and adaptability to adopt CCIs on their MFSs. Furthermore, the commercial downscale reflects their vulnerable livelihoods. Their farming de-intensification due to land and water scarcity and pest and disease incidence negatively affect their livelihood and well-being. Hence, the effects of managerial and business changes are visible over a more extended period and have a higher failure cost for farmers.

Climate-Resilient Innovation Bundles for Farmers' Climate Change Adaptation

This study highlights different innovation bundles farmers can adopt to enhance MFS components' interconnections and respond to CCIs. Good agricultural practices support farmers in increasing yields, reducing crop and animal losses, and sustainably using natural and purchased resources. This results in improving their incomes from crop, livestock, and tree components, and enabling cross-component investments. Circular farming techniques strengthen nutrition exchanges between crops and livestock components. Information bundles provide farmers with relevant information, enabling farmers' timely and wise investment decision-making to improve farm efficiency and support investment connections and technical interactions. Irrigated farming bundles enable farmers' cultivation in the dry season while supplementing crop water needs in the rainy season, increasing farm productivity, incomes, and household nutrition. Value-chain bundles improve farmers' access to input and output markets and family nutrition through improved access to food quantity, quality, and variety. These innovation bundles

are climate resilient, increasing farmers' possibilities and responsiveness to CCIs.

Key Characteristics of Climate-Resilient Innovations

We characterize the climate-resilient innovation bundles' suitability, inclusivity, and adaptability. Suitability reflects these bundles' relevance to farmers' MFS contexts and their innovation needs to respond to CCIs. The bundles gather available solutions and services; some have been tested and showed their best fit to the MFS contexts, such as the solar-based irrigation bundles presented in the section on climate-resilient innovations to support smallholder livelihoods in northern Ghana. The bundles are new but suitable for farmers in NR and NER, as farmers in these regions have similar MFS conditions such as water availability, high radiation, land types and availability, demand segments, and established supply chains for solar-based irrigation investments (IWMI, 2023). Co-developing and scaling such bundles need to involve farmers, other value-chain actors, and stakeholders in analyzing the existing situation and context, identifying and packaging the existing, relevant innovations, products, services, resources, and businesses to address the dynamic CCIs and contextual changes. Applying innovation bundling—a process of combining different technological, social, institutional, financial, business, and process innovations and services at several scales to achieve a desired goal (Ofosu & Minh, 2022a)—enhances the innovation bundle suitability, enabling farmers to respond effectively to CCIs while minimizing trade-offs from their investments in MCLF systems.

Inclusivity emphasizes the bundles' capacity to meet the resources and abilities of different farmer segments to address their CCI needs. Demand segmentation by the private sector helps identify clients' available resources and investment preferences, thereby better targeting different farmer segments with inclusive business models (IWMI, 2023). Inclusivity enhances equitable access for marginalized groups to innovation bundles by addressing multiple barriers. For instance, the irrigation bundle presented under the section on climate-resilient innovations to support smallholder

livelihoods in northern Ghana identifies the demand and supply financial constraints of women, youth, and resource-poor farmers by including PAYGO and PAYOWN services and a water supply business model that enables access for various farmer segments.

Adaptability is the ability of the bundles to be customized to fit into several contexts and to adapt to dynamic contextual changes. Adaptability, for instance, supports the deployment of the irrigated farming bundle mentioned in the section on climate-resilient innovations to support smallholder livelihoods in northern Ghana at several scales, such as the farm, project, country, or cross-country levels (Ofosu & Minh, 2022a). The bundle may also be repackaged to suit several MFSs, such as tree-based systems in SR, vegetable-dominated systems in UER and UWR, and supplemental irrigation requirements in rainfed cultivation in all five regions in NG. Further, the bundles are amenable to farmers using surface water, groundwater, and a combination of surface and groundwater. Adaptability, therefore, highlights the capacity of the bundles to be modified for new contexts, uses, or purposes. Adaptability is strengthened when farmers test and modify innovation bundles to suit their existing farming activities based on their resources and farm management practices.

Multiple Scaling Pathways Supporting the Climate Change Adaptation of Mixed Farming Systems

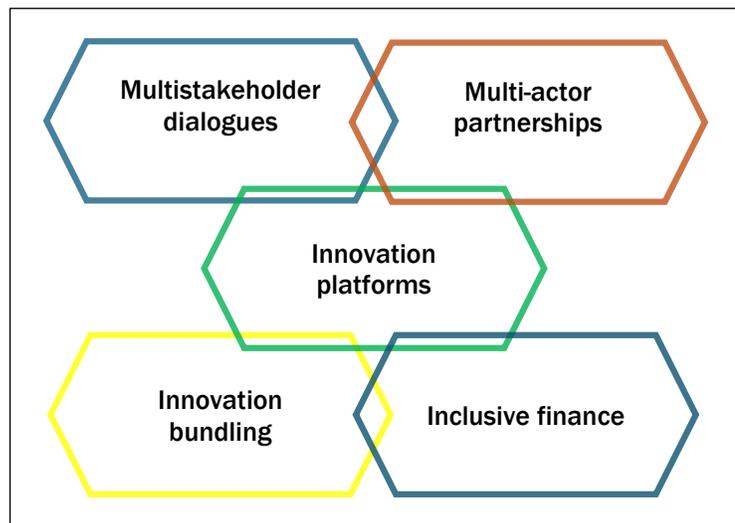
Many opportunities exist to scale climate-resilient innovations to enable farmers' climate change adaptation in the MFS contexts. Multiple stakeholders are growing interested in interventions to address CCIs on MFSs (Abdul et al., 2022; Abegunde & Obi, 2022). There are numerous barriers to scaling climate-resilient innovations, such as poor access to natural, financial, and human capital; group and value-chain dynamics; lack of best-fit innovation bundles; and unfavorable enabling environment (Acheampong et al., 2017; IWMI, 2023; Ofosu & Minh, 2022a). The sustainable climate change adaptation literature

suggests that adaptation should only be integrated into socially and environmentally sustainable development (Magesa et al., 2023). Therefore, multiple pathways are needed to scale climate-resilient innovations for sustainable adaptation of MFSs (Figure 4).

Innovation platforms create spaces for farmers and other actors to develop and invest in actionable solutions that meet their needs (Edlmann & Grobbelaar, 2021). The platforms initiate the identification of bottlenecks, problems, opportunities, key stakeholders, and facilitators, followed by deciding the focus and options for solving challenges while harnessing opportunities, testing and refining solutions, and implementing and scaling up successful solutions to increase adoption, including individual farmers (Schut et al., 2018). Platforms operate at one or several scales, including community, district, national, value-chain, or economic sector. When operating at the community and value-chain scales, innovation platforms develop innovations and solutions that best fit farmers' needs of climate-resilient innovations to respond to CCIs. Bundling different, relevant solutions together enhances the bundles' suitability and inclusivity, as shown in the case of the value-chain and irrigated-farming bundles for the NG MCLT systems.

Innovation bundling provides contextually rel-

Figure 4. Pathways for Innovation Scaling Toward Climate Change Adaptation of Mixed Farming Systems



evant solution bundles for farmers, combining existing and innovative technologies, products, and services (Minh et al., 2024). Social and technical innovations often are not stand-alone solutions, but interact; one may require, or even catalyze, another. Innovation bundling brings synergies to minimize obstacles and trade-offs associated with introducing individual innovations, while minimizing farmers' risk and the private sector's investments (Ofosu & Minh, 2022a). Innovation bundling involves multiple value-chain actors co-developing the bundles with options for farmers and then adapting them to a larger geographical scale. Effective stakeholder interactions, high demand for innovation bundles, and supportive policies and interventions are essential for innovation bundling. The bundling identifies one or more high-demand core innovations, making them accessible to different farmers' investment segments. Core innovations, such as climate-smart seeds, solar-powered pumps, or postharvest techniques, are bundled with complementary solutions—supporting technologies or services—that make the core innovations suitable for the contexts and needs, enabling farmers' investments. One example discussed in this study is the irrigated farming bundles, bundling solar-powered pumps with PAYOWN and PAYGO financial services, and tailoring business models to different demand segments of the NG farmers.

Multi-actor partnerships are formal or informal collaborations between organizations or individuals to strengthen linkages and leverage each other's strengths and resources to address common challenges, maximize opportunities, and leverage synergies for catalyzing innovation. Partnerships can emerge from innovation bundling processes, platforms, or value-chain actor networks. Partners join and invest in partnerships based on agreeing on the collaboration's scope and objectives and members' roles and responsibilities (Maryono et al., 2024). Partners offer knowledge, products, services, and other resources that help to address one or more aspects of challenges associated with catalyzing innovations and investing in new or existing markets, agricultural value chains, and businesses. In scaling irrigated farming bundles for the NG MCLF systems, farmers' financial constraints and

the irrigation equipment suppliers' investment risks are a few of the profound challenges (Ofosu & Minh, 2022b). Scaling partnerships between private-sector irrigation equipment suppliers, government agencies, research organizations, and development actors enable farmers to invest in solar-based irrigation with tailored supply business models and PAYOWN and PAYGO services to diverse demands, mobilizing joint investments in irrigation markets and creating market linkages with digitalizing sales and service networks. Meanwhile, partnerships help to reduce the risk of irrigation businesses by reducing business-to-business transactions, increasing business transparency and outreach, and raising the solar technology market beyond the niche level (Minh et al., 2024).

Inclusive financing involves strengthening the financial ecosystem to accelerate farmers' investment and de-risk private-sector businesses (Minh et al., 2024). Operationalizing inclusive financing in scaling climate-resilient innovation bundles requires identifying demand and supply constraints associated with financing farmers' and agribusinesses' investments, co-developing innovative mechanisms and solutions with finance ecosystem actors to address the constraints, and catalyzing successful solutions to lower farmers' financial barriers at a large scale. Inclusive financing leverages several funding sources to improve financial access for farmers, especially for vulnerable groups, including women, youth, and resource-poor farmers. These sources include blended, concessional, and carbon financing, performance-based subsidies and grants, revolving funds, green bonds, and insurance. For the private sector, inclusive financing improves liquidity by expanding lending to farmers and de-risking their investment in inclusive business models (Minh et al., 2024).

Multistakeholder dialogues are physical and institutional spaces where stakeholders of common interests work together to identify needs, negotiate priorities, develop solutions, mobilize and exchange resources, reach institutional commitment, and build institutional capacity and memories (Minh et al., 2020). By engaging and partnering with multiple stakeholders, multistakeholder dialogues develop sustainable and inclusive scaling pathways, provide and share scaling knowledge and

experiences, and foster interactive learning to benefit the participation of women, youth, and geographically marginalized groups. Operationalized at the macro level, dialogues capitalize on “good scaling practices” for resource mobilization and develop scaling ideas to feasible solutions through “do-reflect-adapt-do” loops. Dialogues can support MFS-related policies and planning processes by sharing experiences and insights into farmers’ responses and innovation needs for climate-change adaptation and facilitating open policy dialogues. When scaling irrigated farming and value-chain bundles in Ghana, multistakeholder dialogues shift a significant investment role onto the private sector while contributing to government and other actors seeking to support farmers’ and marginalized populations’ adaptation to CCIs (Minh et al., 2020).

Some of these innovations have been promoted to farmers in SSA for several years. However, climate change has increased the need for smallholder farmers to modify their systems to meet their needs better. These scaling pathways interact and support each other in the adaptive scaling of innovations for MFSSs’ climate change adaptation. Innovation platforms and bundling support the development of innovation bundles and multi-actor partnerships for scaling the bundles, and vice versa. Inclusive financing further catalyzes the scaling of innovation bundles while supporting innovation platforms and the partnerships’ activities. Multistakeholder dialogues stimulate systemic changes by leveraging several levels of innovation platforms, innovation bundling, inclusive financing, and multi-actor partnerships, facilitating the transformational adaptation in the MFS context. Crucial to scaling climate-resilient innovations toward MFSSs, climate change adaptation safeguards stakeholders’ institutional capacity and memory to ensure continued business and development alignment as we advance.

Conclusion

This study analyzed farmers’ climate change adaptation in mixed crop-livestock-tree (MCLT) system contexts in northern Ghana. Climate change impacts (CCIs) in MCLT systems are visible in

declining soil fertility, yields, productivity, and incomes simultaneously with increasing temperature variability, water scarcity, erratic rainfall patterns, pest and disease incidences, and input costs. These impacts lead to household nutrition and food insecurity, while challenging women’s access to production factors and markets. In response, most farmers focus on combining indigenous and modern farming methods, adjusting agronomic practices, and adapting irrigation management to lower the associated risks. Managerial and business changes in cropping season, de-intensification, livestock management, investment shift, and commercial downscaling negatively affect farmers’ livelihood and well-being over a more extended period. The sustainable and inclusive facilitation of farmers’ climate change adaptation requires multiple pathways to catalyze climate-resilient innovation bundles, such as good agricultural practices, climate information services, irrigated farming packages, and value-chain linkages to combat CCIs effectively.

This study has several implications for policy, development, and research. First, tailoring interventions to diverse innovation needs is essential to support climate-change adaptation strategies that sustainably manage tradeoffs and synergies from farmers’ responses to CCIs in MFSSs. The tailoring requires integrating farmers’ context specificities, leveraging enabling environment factors, and involving private-sector investments and multi-stakeholder support in co-designing, bundling, and scaling climate-resilient innovations. Second, operationalizing systemic approaches to support climate-change adaptation should adopt multiple innovation-scaling pathways to address MFS as a whole and profound CCIs. Collaboration and coordination of efforts must be enhanced to mobilize funding from multiple sources and harmonize interventions while minimizing the duplication and contradiction of efforts. Further research should examine MFS practices under changing climatic conditions in other parts of sub-Saharan Africa to generate holistic insights into climate-resilient innovation bundles and recommendations for sustainable climate-change adaptation. 

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