IS SUSTAINABLE INTENSIFICATION POSSIBLE IN SMALLHOLDER CROP PRODUCTION SYSTEMS IN SEMI-ARID WEST AFRICA? THE CASE OF THE RED VOLTA AND BLACK VOLTA BASINS IN NORTHERN GHANA

PRINCE ANSAH

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SUPERVISORS: Professor Mark New (University of Cape Town)
Dr. Marieke Norton (University of Cape Town)

DEDICATION

To my loving wife, Pearl Jacker Doe, whose unwavering encouragement was my guiding light throughout this journey; to my parents, Mr. and Mrs. Ansah, whose prayers fortified my spirit and resolve; and to my esteemed supervisors, Prof. Mark New and Dr. Marieke Norton, for their invaluable guidance and mentorship. This work is a testament to your collective belief in me.

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ABSTRACT

Food systems experts consider Sustainable Intensification (SI) a key concept to tackle the increasing global and regional food demand, particularly in semi-arid West Africa, which is prone to socioeconomic and biophysical challenges. In Ghana, crop production varies across semi-arid systems, particularly between the Red Volta and Black Volta basins. Given this context, the study assessed and compared the factors contributing to crop productivity differences between and within the RVB and the BVB and explored how these factors contribute to achieving SI goals of productivity, resilience, efficiency, and equity. This study applies an integrated SI framework and case study approach in these basins, using mixed methods: 200 household surveys, six in-depth interviews, three focus group discussions, five key informant interviews, and two workshops, with both random and purposive sampling. The results identified several important determinants of crop productivity that are relevant to SI. These included water/soil-related risks and strategies, access to agricultural resources, demographic characteristics, institutional collaboration, and household production needs. These determinants, which differ in importance within each basin, impact the achievement of SI goals. Farmers' perceptions of water/soil-related risks have a direct bearing on crop productivity across basins. Access to consistent resources was found to enhance yields, though an over-reliance on sporadic government support posed challenges especially in RVB. Demographic factors, notably age, gender, and education, emerged as significant determinants of farming practices and outcomes. Furthermore, the research emphasized the importance of robust inter-institutional collaboration in bolstering agricultural innovation and productivity. Notably, the choice of crops cultivated was influenced by a delicate balance between household consumption needs and market demands. The study underscores the need for local institutions to mitigate weak policies, limited resources, and poor knowledge transfer that could inhibit SI strategies implementation. The thesis concludes by recommending that national and local agriculture stakeholder should promote the SI concept as a guiding principle for improving existing farming systems through strengthening agriculture policies and facilitating innovations within smallholder crop production systems to enhance sustainable productivity in semi-arid Northern Ghana.

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LIST OF ABBREVIATIONS

ADB	African Development Bank
AEAs	Agriculture Extension Agents
AIS	Agriculture Innovation Systems
BVB	Black Volta Basin
CA	Conservation Agriculture
CIKOD	Centre for Indigenous Knowledge and Organisational Development
CPD	Changing Planting Dates
CSA	Climate Smart Agriculture
CSOs	Civil Society Organisations
DOA	Department of Agriculture
DS	Dry Spells
DSN	Depleted Soil Nutrients
ER	Erratic Rainfall
FAO	Food and Agriculture Organisation
FAW	Fall Armyworm
FBOs	Farmer Based Organisations
FGDs	Focus Groups Discussions
GDP	Gross Domestic Product
GIDA	Ghana Irrigation and Development Authority
GIZ	Gesellschaft fur Internationale Zusammenarbeit
GMOs	Genetically Modified Organisms
GSS	Ghana Statistical Service
GSW	Gender and Social Welfare
IFDC	International Fertilizer Development Center
IPCC	Intergovernmental Panel on Climate Change
KIIs	Key Informant Interviews
LSM	Limited Soil Moisture
MLR	Multiple Linear Regression
MOFA	Ministry of Food and Agriculture

MOTIFS	Monitoring Tools for Farm Sustainability
NGOs	Non-Governmental Organisation
OECD	Organization for Economic Cooperation and Development
OPV	Open Pollinated Varieties
PFJ	Planting for Food and Jobs
POMC	Poor Organic Matter Content
PRISE	Partnership for Rural Innovation and Sustainable Environment
RAAIS	Rapid Appraisal of Agriculture Innovation Systems
RVB	Red Volta Basin
SAFA	Sustainability Assessment of Food and Agriculture
SD	Standard Deviation
SGD	Sustainable Development Goals
SI	Sustainable Intensification
SIPs	Sustainable Intensification Practice
SSA	Sub-Saharan Africa
SWI	Scarce Water for Irrigation
UCT	University of Cape Town
UER	Upper East Region
UWR	Upper West Region
VSLAs	Village Savings and Loans
WAP	Women in Agriculture Programme/Project
WEF	World Economic Forum

CHAPTER 1
INTRODUCTION

1.1 Introduction

Food demand is expected to increase at both global and regional levels as the rate of socioeconomic drivers on demand, such as population growth and prosperity, outpace food supply, while biophysical constraints, including climate change and poor soils, continue to challenge crop production systems, especially in semi-arid areas of developing countries (IPCC, 2022; van Loon et al., 2019). The solutions to meet food demand with supply have been controversial among experts. However, the concept of Sustainable Intensification (SI) is receiving attention as a way of enhancing existing food production systems to meet food demand along with minimal or no impact on the health and functionality of agriculture systems (Campbell et al., 2014; Cassman & Grassini, 2020; Garnett et al., 2012).

Ghana's food crop sector has struggled to meet production targets outlined in national agriculture policies over the years, especially for production systems in semi-arid Northern Ghana. Crop production in semi-arid Northern Ghana has been historically low, with increased production often achieved through extensification, where land expansion increases overall productivity. However, low productivity in semi-arid Northern Ghana is more notable in the Black Volta basin (BVB) than in the Red Volta basin (RVB). This study seeks to understand the factors contributing to the low productivity in the BVB compared to the RVB and examine how these factors can inform future SI practice, policy and research. Practically, what is possible regarding implementing SI is context-specific (IPCC, 2022), and the need to understand specific geographic cases is critical to developing evidence on the subject.

This introductory chapter provides the background context of SI as a proposed solution to global and regional food production problems, discusses the problem statement of low productivity in BVB versus RVB, outlines the research aim and specific objectives, justifies the study's significance and introduces the overall structure of the thesis.

1.2 Background

The global food system is under pressure from biophysical and socioeconomic factors, including population growth, increased urbanisation, a widening middle class, and climate change (Cassman

& Grassini, 2020; IPCC, 2022). Even though global crop production continues to increase or, in some crops, remain stable, the food demand driven by socioeconomic factors like population, economic and urban growth rates is outpacing crop production levels for major staple food crops, including maize, rice, wheat and soybean (Cassman & Grassini, 2020; Dekeyser et al., 2020; IPCC, 2022; WEF, 2017). Future projections indicate that, without adaptation, climate change will intensify water scarcity, degrade soils and ecosystems, and accelerate biodiversity loss, affecting the global food system, especially in arid and semi-arid regions (IPCC, 2018; Sultan & Gaetani, 2016). As global food demand increases under harshening environmental conditions, it will affect the food and livelihood security of millions of people in developing countries that rely on agriculture (Godfray et al., 2010; WEF, 2017). Most scholars agree that increasing crop productivity to meet current and future food demand is necessary and will require an intensified production system to achieve that goal (Godfray et al., 2010; Pretty et al., 2011). However, controversies surround proposed pathways to achieving intensified crop production systems. Some scholars suggest that food production that meets global demand can be achieved through enhanced technology inputs (seed, fertilisers, and machinery) without land expansion. In contrast, others argue for gradually expanding crop production into untapped arable lands (Pretty et al., 2011).

Nevertheless, SI has emerged as an attractive approach that attempts to address the growing gaps between demand and production (Godfray et al., 2010). According to Garnett et al. (2012), SI is widely defined as *"a form of production system wherein yields are increased without adverse environmental impact and without the cultivation of more land"*. In other words, SI seeks to increase crop production without land expansion while efficiently managing production inputs with minimal or no impact on the biophysical properties of existing agriculture systems (Campbell et al., 2014; Garnett et al., 2012; Musumba et al., 2017). More recently, the SI concept has gradually evolved to include the achievement of positive socioeconomic and livelihood outcomes, such as income generation, access to inputs/services and equity among social groups that affect the agriculture system as a whole (Cassman & Grassini, 2020; Musumba et al., 2017; Pretty et al., 2011). See **Figure 1** below. In principle, an SI food production system must ensure productivity, resilience, efficiency, and equity. In developing countries, where access to land is a critical factor of production combined with degraded soils, climate change, poverty and population growth, SI could enhance the biophysical and socioeconomic properties within the food production system to ensure food security and socioeconomic development (Campbell et al., 2014; Pretty et al., 2011; Schut, Rodenburg, Klerkx, Kayeke, van Ast, et al., 2015).

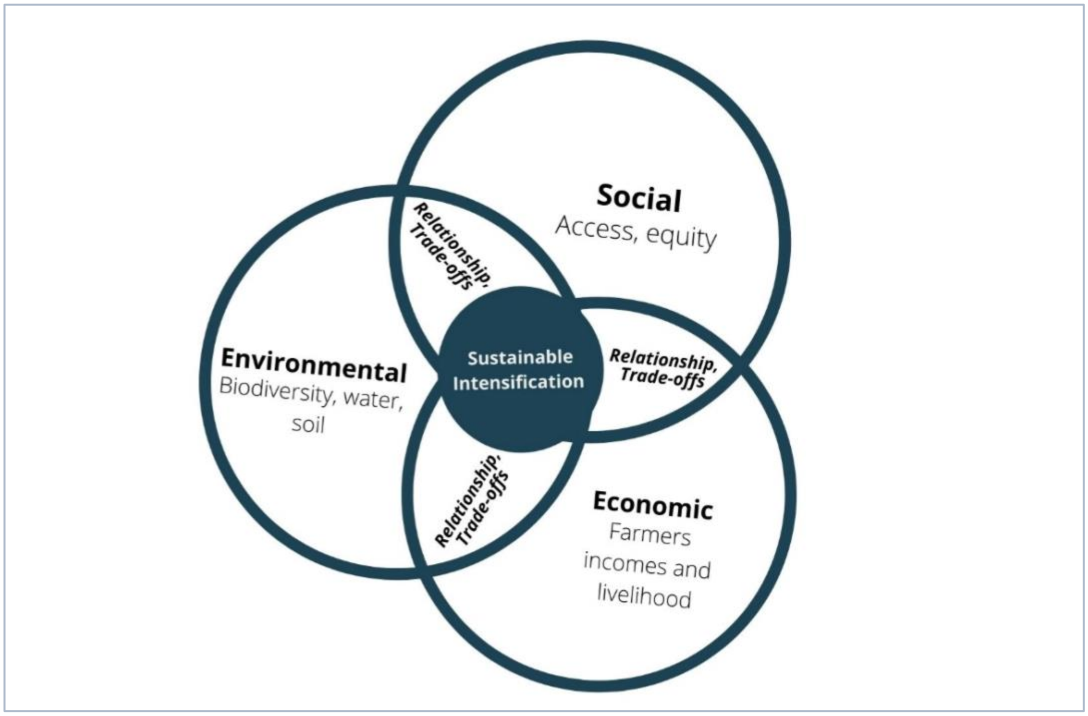

***Figure 1**: Sustainable Intensification dimensions/pillars adopted from* Garnett et al. (2012) and Pretty et al. (2011).

In West Africa, agriculture is an important economic sector that contributes 35% of the regional gross domestic product (GDP) and is a key livelihood option, employing about 66% of the total population and about 81% of the rural population (ADB & FAO, 2015; Allen et al., 2018). Beyond this importance, agriculture in West Africa faces numerous biophysical and socioeconomic constraints that hinder the sector's growth, especially for semi-arid crop production systems (Padgham et al., 2015). The semi-arid crop production system of West Africa is a natural resource-limited environment that efficiently manages the fewer biophysical resources such as water, soils, and biodiversity for crop productivity (Blein et al., 2008; Padgham et al., 2015). Socioeconomic constraints such as a high population growth rate, urbanisation, and a widening middle class will complicate the existing biophysical pressure on agriculture systems in West Africa, especially in semi-arid areas, tripling food demand by 2050 (van Loon et al., 2019). An increase in food demand will exacerbate other socioeconomic challenges like rural-urban migration and further extensification of agriculture systems as land use demand for food production increases in the region (ADB & FAO, 2015b; OECD & FAO, 2016). The major biophysical constraint relates to the climate-sensitive nature of the regional economy, where key development sectors, especially agriculture, rely heavily on rainfall (FAO, 2014b). Beyond impacts on agriculture systems, evidence shows that climate change intensifies existing complex socioeconomic constraints, including population growth, inequality, poverty, conflicts, migration, and hunger within these semi-arid economies (Chauvin & Mulangu, 2012; IPCC, 2022; Jalloh et al., 2012).

Ghana's agriculture sector has struggled to meet its potential growth rate targets outlined in the different agriculture policies (Diao & Hazell, 2019; Mawunyo & Woedem, 2013; World Bank, 2017). For instance, during 2010 - 2016, the sector failed to meet the 6% growth rate target in the Food and Agriculture Sector Development Policy (FASDEP II) despite a 3% per annum population growth rate and over 50% of employment dependent on the sector (Amisigo et al., 2015; FAO, 2015; MOFA, 2017). Even though the agriculture growth rate has increased since 2017, its share of the total GDP has declined compared to the industry and services sectors of the economy which have gained momentum (MOFA, 2017; World Bank, 2017). Furthermore, within the main agriculture sub-sectors, the crop sector has had the highest growth rate since 2011 compared to other sub-sectors like fisheries, livestock and forestry (Mawunyo & Woedem, 2013; MOFA, 2017; World Bank, 2017). However, about two-thirds of the crop sector growth rate is from cocoa production, while staple cereal crops like maize, millet, rice and sorghum saw a reduction in productivity from 2011 to 2017 (MOFA, 2017; World Bank, 2017). The challenges to the growth of the agricultural sector, especially for cereal production, are predominantly: the rain-fed production system with low irrigation development, the use of hand tools for over 80% of output, and over 80% of production for subsistence purposes (Amisigo et al., 2015; Chauvin & Mulangu, 2012; FAO, 2015). In addition to these challenges, the climate-sensitive nature of Ghana's agriculture system, coupled with poor soils and land degradation, have played crucial roles in hindering the sector's development and affecting the overall productivity output in some areas, especially semi-arid regions (Amikuzino & Donkoh, 2012; Pinto et al., 2012). However, the biophysical and socioeconomic challenges and their impact on Ghana's agriculture sector, especially crop production, may differ depending on the geographical and ecological context (Mawunyo & Woedem, 2013; World Bank, 2017).

1.3 Problem Statement

In Northern Ghana, agriculture is the primary livelihood activity supporting millions of households in the region. However, numerous biophysical and socioeconomic factors make agriculture challenging for smallholder farmers to meet their crop production targets, especially within semi-arid areas of RVB and BVB. The production of staple crops like maize in these basins has struggled to compete with the production averages for similar staple crop production systems elsewhere in the country. Even though crop productivity is not encouraging in both basins, the average productivity estimate for two decades (1997 to 2017) in BVB (3.3 mt/ha) is under half of the national average (6.7 mt/ha) over the same period (MOFA & GSS, 2019a). Similarly, observed crop productivity estimates for fifteen years (2005-2019) in BVB (3.8 mt/ha) were lower than the productivity estimates in RVB (7.5 mt/ha) over the same production period (MOFA & GSS, 2019a). Even though productivity in BVB was less over the fifteen years, land use estimates for crop production over the same period were higher than that of RVB. For instance, the average cultivated area for crop production in BVB from 2005 - 2019 was 14% more than that of RVB, yet the estimated crop yield (mt/ha) over the same period was 49% less (MoFA & GSS, 2019a). **Figure 2** below shows crop productivity levels between the RVB and BVB from 2005 to 2019.

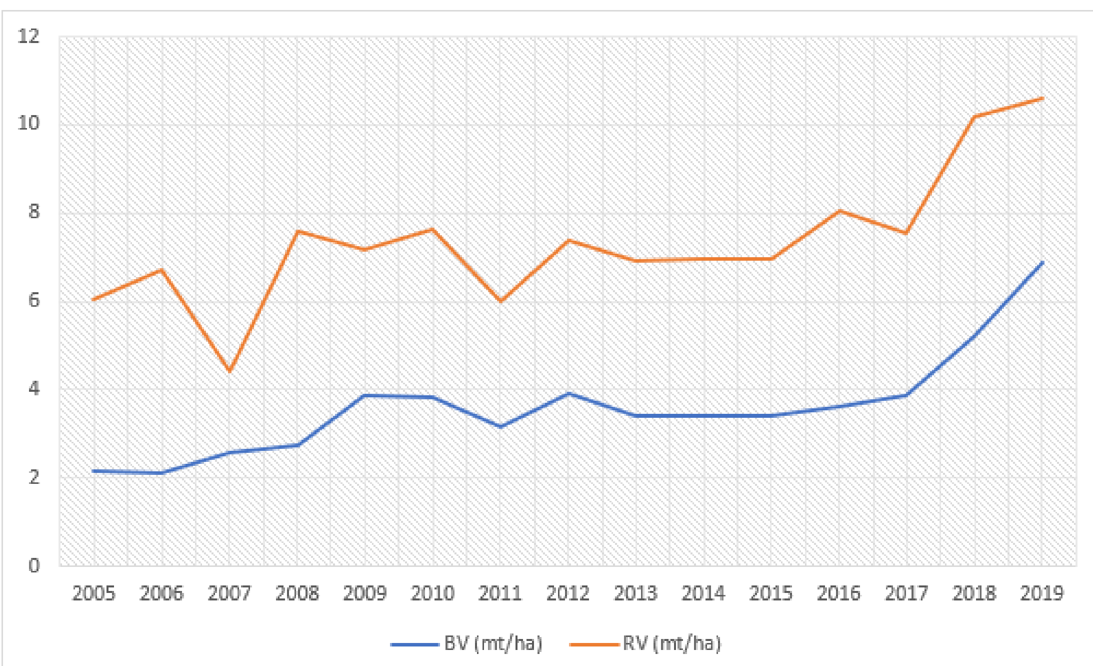

***Figure 2**: Crop productivity estimates from 2005 to 2019 between RVB and BVB. Source: (MoFA & GSS, 2019). Crop yields estimate data retrieved from the Ghana government's open-source data portal.*

Furthermore, productivity from irrigated dry season farming in BVB remains the lowest compared to RVB and other parts of the country. For instance, in 2015, the BVB catchments recorded the least irrigated productivity in the country, with 0.7mt/ha, compared to productivity in RVB catchments, with 7.4mt/ha (MoFA, 2016). These productivity estimates indicate how the current cropping systems in semi-arid Northern Ghana have failed to match national averages, especially in BVB, where productivity is significantly lower than RVB. These low productivity outcomes in rainfed and irrigated systems demand an urgent and innovative cropping system response like SI that can potentially increase crop productivity with limited biophysical and socioeconomic costs.

According to van Loon et al. (2019), the interaction between biophysical and socioeconomic factors can help explain productivity differences between locations with otherwise similar characteristics. Even though a biophysical factor such as rainfall has been lower in the BVB than RVB for the past decade (2009 – 2020), the average difference is not substantial enough to explain the observed crop productivity difference (DOA-Bongo, 2020; DOA-Lawra, 2020). Socioeconomic factors like household size, institutional structures, demography, access to agriculture resources, social networks, migration, and off-farm economic activities (alternative livelihood sources) can influence crop production systems and determine productivity levels (Amisigo et al., 2015; Descheemaeker et al., 2010). Despite these biophysical and socioeconomic constraints, there is the potential to intensify agriculture in semi-arid Northern Ghana through appropriate sustainable agriculture practices at the farm, household and community levels (Amisigo et al., 2015; Dekeyser et al., 2020; IPCC, 2022).

Previous research in Ghana and West Africa (Dakyaga et al., 2020; Hoeschle-Zeledon, 2021; Kotu et al., 2017) has mostly sought to understand low productivity in semi-arid agriculture systems by focusing on a single-factor approach. This approach means researchers had to examine low productivity through either biophysical lenses, such as climate change and soil quality research or socioeconomic lenses, such as gender and off-farm influence on crop productivity. Even though findings from a singular-factor approach can provide detailed evidence on the causes and effects of low productivity, they often miss the critical interactions/relationships that occur within multiple-factor approaches, which could provide a more holistic overview of the agriculture system. Some previous studies in semi-arid Northern Ghana, including climate change adaptation research, combined multiple factors but often lacked comparative analysis, explaining some context for low productivity. Moreover, the concepts adopted for most crop productivity research are rarely action-oriented, where the research findings are easily applicable for practice or policy implementation. Through SI research, where multiple factors to crop productivity are assessed and compared, researchers can address these gaps within low-producing semi-arid agriculture systems and provide pathways for sustainable smallholder farming.

This research will explore why crop productivity differs between and within the RVB and BVB by evaluating their biophysical, socioeconomic, and institutional characteristics in terms of influence on crop productivity and then exploring which of these factors further support or challenge SI goals/principles. The case areas in RVB (Bongo Municipality) and BVB (Lawra Municipality) were selected for the comparative study due to their similarities in land size (about 500 km^2), location (transboundary catchments between Ghana and Burkina Faso), and ecological zone (semi-arid region).

1.4 Research Aim, Question, and Objectives

1.4.1 Research Aim

To determine the factors contributing to productivity differences between RVB and BVB and how these factors could influence the implementation of SI within smallholder agriculture systems in semi-arid Northern Ghana.

1.4.2 Research Objectives

1. Assess and compare the biophysical characteristics that determine crop productivity and could enable or hinder the implementation of SI among smallholder crop production systems in semi-arid RVB and BVB.
2. Assess and compare smallholder farmers' socioeconomic characteristics that determine crop productivity and livelihood outcomes between the RVB and BVB, which could enable or hinder the implementation of SI among smallholder crop production systems in the region.
3. Investigate and compare the institutional constraints and entry points for implementing SI within smallholder crop production systems in semi-arid RVB and BVB.

1.5 Research Justification

The study is relevant for progressing the concept of SI within smallholder agriculture systems by advancing existing knowledge, providing practical tools for practice, and delivering the needed guidelines for policy formulation on agriculture in semi-arid Ghana.

The present study enhances the knowledge of factors contributing to SI in dry areas of West Africa. It draws new insights into the various characteristics that can hinder or progress sustainable farming among smallholder farmers. The study's findings significantly contribute to the existing knowledge relevant to SI in semi-arid areas of West Africa, including factors that influence crop productivity, resilience to biophysical risks and efficiency in the use of agriculture resources. Most SI research limits its scope to the biophysical and socioeconomic domains; this study expands the approach to SI research by including an analysis of institutional structures within the agriculture system as an additional domain to illustrate how its characteristics could be entry points for innovation for SI among smallholder farmers. Furthermore, due to the inequalities and disparities among social groups perpetuated by cultural norms in the study area, the present study evaluates the importance of equity within the agriculture system as a critical goal to achieve SI in the case study areas.

The comparative nature of this study could be the first case study to compare the crop production systems in different semi-arid areas of Northern Ghana using the SI framework. The various methodological tools used for the data collection in this study are interdisciplinary and participatory, which is different from the tools used in most SI studies. The data collection tools employed for the study included qualitative and quantitative approaches and primary data collection (workshops, focus group discussions, surveys and key informant interviews) and secondary data analysis (rainfall, soil analysis and pest infestation data) from RVB and BVB. The study provides a systematic method and mode for data collection, which researchers can follow or modify for future SI research in dry areas of West Africa.

The present study is relevant for SI practice at the farm, household, community, and basin levels. The study provides detailed characteristics of the social groups most vulnerable to biophysical and socioeconomic challenges at the household, community, and basin levels and the specific interventions needed to respond efficiently. These findings can support local institutions with the blueprint to identify the smallholder farmers in semi-arid Northern Ghana who may need the most capacity or resource support for SI practice.

Furthermore, the study's findings can help stakeholders reimagine the productivity of the agriculture system as an interaction between biophysical, socioeconomic, and institutional dimensions, such that an impact of one dimension affects the others. This thinking could help stakeholders implement SI strategies that are innovative enough to address multidimensional challenges within the agriculture system. The subsistence nature of most smallholder farming systems in Northern Ghana makes farmers more focused on sustaining crop productivity and less concerned with environmental sustainability. This study provides the needed guidelines for stakeholders to implement balanced agriculture interventions that provide a win-win outcome for crop productivity and environmental sustainability for the smallholder agriculture systems.

Moreover, the findings from this study provide guidelines for local and national agriculture policy implementation. SI requires policies that support adequate extension service contact, input use efficiency, alternative livelihood options, and access to resources that include credit, financial services, and information. This research is relevant for policymakers to guide them in enacting agriculture policies that ensure equitable and affordable distribution of inputs and services across social groups and regions. The study provides profiles of social groups that may need more engagement and dialogues during the policy formulation and implementation stages. These social profiles enable stakeholders to identify the policy needs, the target beneficiaries, and the processes to implement such policies to achieve SI goals. For instance, knowing the most vulnerable and empowered social groups through this study can help policymakers design equitable policies and programmes that serve the needs of all social groups within the agriculture system.

1.6 Thesis Structure

This thesis is organised into eight (8) chapters, as follows;

i. Chapter One of the study introduces the thesis, a background to SI as a solution to global food demand, the problem statement of low productivity in the BVB than RVB and the outline of the aim and research-specific objectives regarding barriers and enablers for SI. The chapter continues with the justification/significance of the study for advancing future research, practice, and policy and concludes with the structure of the study.

ii. Chapter Two presents a literature review of topics relevant to the research, which include the introduction to the literature discussions, the global food systems, the evolution of Agriculture in West Africa and Ghana, Sustainable farming systems, characteristics of crop productivity in West Africa/Ghana that contributes to SI outcomes and the methodological review.
iii. Chapter Three presents the methodologies used in the research, including the conceptual framework, the research design, the guidelines for selecting SI indicators, the data collection stages and the data analysis procedure.
iv. Chapter Four presents the background of the study area and respondents, including the study areas' profiles, the respondents' biographical data and the outcome of indicator validation.
v. Chapter Five compares the biophysical characteristics of crop production systems (Objective One) in the RVB and BVB. The main sections include the results, analysis, and discussion of themes related to biophysical risks and responses (strategies) as barriers or enablers for achieving SI goals.
vi. Chapter Six compares the socioeconomic characteristics (Objective two) in the RVB and BVB. The main sections include the results, analysis and discussions on crop type, cropland, crop productivity levels, incomes, off-farm activities, and access to resources as barriers or enablers for achieving SI goals
vii. Chapter Seven compares the institutional characteristics (Objective three) in the RVB and BVB. The main sections include results, analysis and discussions on institutional constraints, relationships, entry points, and strategies as barriers or enablers for achieving SI goals.
viii. Chapter Eight concludes the study by outlining the overall key findings, the significance of the study, study limitations, general recommendations (for practice, policy and research) and plans for disseminating the study findings.

1.7 Summary

Biophysical and socioeconomic risks, including climate change, poor soils, population growth, increased incomes, and urbanisation, threaten the Global food systems. These threats to the food system may exacerbate food and livelihood security for millions of households that depend on agriculture, especially in developing countries. Sustainable solutions to future food production challenges have been controversial as some scholars propose land expansion while others propose input intensity to meet food demand. Sustainable Intensification of the agriculture system is the latest concept that combines increased crop production with resilience, efficiency, and equity as principles or goals to meet current and future food demand. Over 15 years, semi-arid Ghana's RVB agriculture system produced less under more significant land expansion than the BVB agriculture system with similar geographical and ecological characteristics.

The study aimed to determine the factors contributing to productivity differences between RVB and BVB and how these factors could influence the implementation of SI within smallholder agriculture systems in semi-arid Northern Ghana. The study's objectives compared the biophysical, socioeconomic, and institutional characteristics between RVB and BVB to identify factors for productivity differences and how those factors can enable or hinder SI crop production systems in semi-arid Northern Ghana. The study is helpful for future research, practice, and policymaking within the agriculture sector at the local and national levels.

Finally, the study is in eight chapters, with chapter one introducing the research, chapter two review of previous research, chapter three methodological approach used, chapter four background information on the study area and respondents, and chapters five, six and seven presenting the results, analysis, and discussions of objectives one, two and three respectively and with chapter eight as the conclusion of the study.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

This PhD has aimed to determine the factors contributing to productivity differences between RVB and BVB and how these factors could influence the implementation of SI within smallholder agriculture systems in semi-arid Northern Ghana. The study's objectives are to assess and compare the biophysical, socioeconomic and institutional characteristics of the smallholder agriculture system that could hinder or enable SI in Northern Ghana. This chapter presents and reviews the existing literature on factors that are known to hinder, enable and sustain crop production systems at the global, regional and national scales. The types of literature used were mostly peer-review articles, technical reports (by organisations with established track records of research and practice in agriculture), books and conference proceedings. The materials for the review were electronically sourced using online database platforms such as Primo (UCT library online database), the Web of Science and ScienceDirect, and searching reference lists of such publications. The aim and objectives of the present study provided guidelines for the outline of the literature review and the key search words used. Except for a few articles, the literature selected for this review ranged from publications dated January 1, 2010, to July 30, 2022.

The literature review is organised into 5 main sections. The first section describes the current state of the global food production system, the challenges it is facing, and suggested ways forward. The second section tracks the historical evolution of food production systems/agriculture and the factors that led to its phases in semi-arid West Africa and Ghana. The third section reviews existing knowledge on the types of cropping systems in West Africa/Ghana, including the conventional and sustainable ones. The fourth section explores the literature around SI, including the characteristics (pillars and indicators) that hinder or enable crop productivity in Northern Ghana. The fifth and last section assesses the methodological procedure used in previous studies for assessing SI. This section also describes the conceptual framework for the study.

2.2 The global food production system

The global food production system has been the source of food security, nutritional needs, employment, and a means for poverty reduction for millions of people worldwide, especially in developing countries (Godfray et al., 2010; WEF, 2017). Several studies have shown that the global food production system has improved over the past several decades, enhancing food security and significantly reducing hunger and malnutrition (Ericksen, 2008; WEF, 2017). The productivity increases have led to increased supply beating down food prices and making food accessible to more people (Godfray et al., 2010). In the developing world, researchers have documented considerable evidence of the food production system as a livelihood opportunity to reduce poverty for many households (Brouwer et al., 2020; Okpala, 2020). Even though the food production system has advanced in recent years, some scholars have questioned the long-term environmental and socioeconomic impacts of the dominant production systems of agriculture intensification, extensification and the corporate takeover of the supply chain to meet the global demand (Ericksen, 2008; Okpala, 2020).

Ericksen (2008) argues that agriculture intensification, often practised in developed countries to increase productivity, may also increase water and soil pollution and enhance greenhouse gas emissions through intense machinery, inputs and agrochemical application. For instance, a global report shows that agricultural intensification has degraded about a third of global arable lands, which may affect future production (WEF, 2017). On the other hand, most developing countries meet food demand by expanding land to grow more food (Brouwer et al., 2020). Consequentially, food production by extensification can lead to biodiversity loss, natural resource degradation and increased greenhouse gas emissions (Godfray et al., 2010; Wiebe et al., 2017). The increased demand for food and the commercialisation of agriculture has invited a corporate takeover of the supply chain, which has become the dominant activity of the global food production system rather than farming (Ericksen, 2008).

The significant factors driving food demand at the global level include population growth, the expansion of the middle class and urbanisation (de Bruin & Dengerink, 2020). Several studies have predicted that these drivers of food demand will increase the pressure on current and future food production systems (Dekeyser et al., 2020; Godfray et al., 2010; WEF, 2017). For instance, forecasts show that the global population will hit 8.5 billion by 2030, with more than half of the population (4.9 billion) expected to be in the middle class and living in urban areas, and it is expected that the demand for food will increase to challenge the existing food production system, especially in developing countries (de Bruin & Dengerink, 2020; WEF, 2017). However, productivity in developing countries is done by farmers with limited resources responsible for meeting about

80% of the food needs of billions of people, which could affect future food production (Okpala, 2020; WEF, 2017).

Beyond the drivers of demand, environmental challenges, including climate change, water scarcity, and soil degradation, are increasingly affecting global production levels (Dekeyser et al., 2020; Godfray et al., 2010; WEF, 2017). The IPCC (2022) emphasises that climate change will disrupt food production systems by reducing yields of major food crops like maize, millet, sorghum and rice for most agriculture-dependent countries in the developing world, especially in Asia and sub-Saharan Africa. The impact of climate change on global food production systems implies that food security and nutritional needs will become a problem for millions of people living under the poverty line (Dekeyser et al., 2020; Ericksen, 2008). Also, natural resources such as water, soil and biodiversity that support the food production system are under threat due to the impacts of climate change (Dekeyser et al., 2020). For instance, rainfall variability and drought have implications for surface water and groundwater recharge, as future projections indicate that by 2050 groundwater recharge may reduce by 70% in some areas (IPCC, 2022). Other factors, including access to resources (information, land and farm inputs), especially for women farmers in developing countries, challenge the food production system to fully meet its potential (Brouwer et al., 2020).

A growing body of literature maintains that these complexities require solutions that enable the food production system to handle these environmental and socioeconomic challenges to sustain food production and meet demand targets (Brouwer et al., 2020). Dekeyser et al. (2020) argue that a sustainable food production system should contribute to maintaining the biophysical and socioeconomic properties that enable the food production system to function. Previously, most scholars tackled sustainable food production systems using linear approaches, where a single domain (either biophysical or socioeconomic) was used to evaluate the food production system to achieve the desired food security and poverty reduction outcomes (Brouwer et al., 2020; Ericksen, 2008; Okpala, 2020). In recent years, an integrated approach to a sustainable food production system has gained mainstream support from many scholars, creating a win-win outcome for achieving socioeconomic and environmental outcomes (Brouwer et al., 2020; Dekeyser et al., 2020; WEF, 2017). In an integrated approach, the expected socioeconomic outcomes (besides meeting food security and income needs) include equity of opportunity and resources, such as information, farm inputs and agriculture services. The environmental outcomes include the efficiency in the use of natural capital (including water, soils and biodiversity) and resilience of this capital against biophysical-related risks such as climate change (Godfray et al., 2010).

Overall, the evidence presented in this section suggests that most scholars agree on the progress made in the global food production system over the years while recognising the associated challenges and the need to pursue new pathways to sustain productivity to meet future demand. However, some authors are critical of the global perspective of the food production systems and argue from a localised context, as the pattern and characteristics of production systems differ based on regional development (Okpala, 2020; Dekeyser et al., 2020; WEF, 2017).. From the presented literature, there are indications that socioeconomic challenges such as population and urbanisation growth rates coupled with less capacity to cope with environmental impacts make the pathway to sustainable food production systems in developing countries different from that of developing economies. Resolving these complexities within developing economies like West Africa will require an integrated food production system approach that draws on a global food sustainability concept like SI and applies it locally. The next sections attempt to understand how previous studies have described and dealt with these complexities within the West African food production system as they have evolved over time and whether a global concept like SI can find a place within a localised context in Northern Ghana.

2.3 Evolution of crop production systems in West Africa

Little is known about the genesis of crop production in West Africa, which has generated many theories of how agriculture evolved in the region (Ugwuja, 2018). These theories are due to the limited knowledge of early migratory patterns, the culture of the first settlers, and the region's environmental conditions (Manning, 2018). According to some scholars, the expansion of agriculture in West Africa might have begun with the adaptation of the earliest cultivators (pastoralists) to their habitat (Ozainne et al., 2014). Existing evidence suggests that agro-pastoralism was the first form of complex farming system practised by early inhabitants, mainly in the southern Sahara (Manning, 2018; Ozainne et al., 2014; Sissoko et al., 2011). As noted by Manning (2018), this earliest system led to the spread of pearl millet (the first known domesticated crop in West Africa) between 3000 BC and 1000 BC, which was an indication of the earliest migration patterns leading to an established crop production system in the region. Subsequently, agropastoralists became more innovative to survive the desiccation of their ecosystem through domestication and cultivation of pearl millet (*Pennisetum glaucum*), cowpea (*Vigna unguiculata*) and fonio (*Digitaria exilis*) and production of livestock (cattle, goats and sheep) around 2200 BC and before the second millennium (Ozainne et al., 2014). Manning (2018) concludes that the spread of these earliest domesticated crops in the region was primarily due to cultural and environmental factors that enabled the migration of pastoral activities from northern Africa to the rest of sub-Sahelian West Africa. Even though a body of literature describes cultural events, migration patterns and climatic events as the causal link and exclusive indicators to understanding how the crop production system spread in West Africa, they may not be the only reasons for its earliest development.

In examining the agriculture system before the colonial era, Inikori (2013) found that crop production in West Africa was predominantly subsistence but commercially more viable than in most parts of Africa. He identified that while early cultivators in West Africa were strictly subsistence with no commercial interest, they could not be self-sufficient in producing everything needed; they reserved some as an exchange for cash or other produce (Inikori, 2013). By the 19th and 20th centuries, agriculture was the main economic activity across the region, and the exchange of one type of agricultural produce for another was very common (Ugwuja, 2018). Crop farmers, predominantly in the South of the region, exchanged crops for meat and dairy products such as milk from pastoralists who travelled with their herd from the North across other parts of the region (Ugwuja, 2018). The most prominent evidence of this was Senegambia, where grain farmers produced about 25kg per capita above what they consumed, and pastoralists consumed 53kg above what they produced over 100 years from 1850 to 1950 (Inikori, 2013). During the colonial period, labour-intensive crops, including palm oil and cocoa in the south and groundnut and cotton in the North, gained prominence in West Africa due to their commercial and export value in the transatlantic trade (Austin, 2009). However, the post-colonial crop production system in the region remained largely subsistence and is likely to continue as a significant livelihood activity (Inikori, 2013).

In their work, Sultan and Gaetani (2016) recognised that agriculture in West Africa in the 21st century faces numerous biophysical and socioeconomic challenges that could hinder the sector's needed growth. The predominantly rain-fed agriculture system in the region has been significantly affected by drought events and climate change (IPCC, 2018; Sultan & Gaetani, 2016). After favourable climatic conditions during the beginning to mid-20th century, the region experiences severe drought periods in the 1970s and 1980s, and has not fully recovered (Sissoko et al., 2011; Sultan & Gaetani, 2016). According to Sissoko et al. (2011), climatic conditions during these periods led to high rainfall variability, especially in arid and semi-arid areas and a rainfall regime change that shows fewer but more intense rainy days related to extreme events (Sissoko et al., 2011b; Sultan & Gaetani, 2016a). The occurrence of extreme biophysical/climatic events throughout the end of the 20th century has been partially or fully associated with the historic food crises (1974, 1984/5, 1992, 1996, 2002) in the region that required external food aid (Sissoko et al., 2011; Sultan & Gaetani, 2016). The need to reimagine agriculture with the potential impact of biophysical challenges such as climate change and climate variability has been an enormous development and policy issue in the 21st century (Sultan & Gaetani, 2016a). Other biophysical challenges, including infertile and degraded soils in the region, have also been challenging, especially in semi-arid areas (Sissoko et al., 2011). Socioeconomic factors such as increasing population, access to resources, migration, expansion of urban areas, income improvement, and growing middle class also contributed to the region's food production dynamics (ADB & FAO, 2015; Allen et al., 2018).

Even though both biophysical and socioeconomic factors have deepened the complexity and evolution of agriculture in West Africa over three decades (starting from 1980 to 2012), subsistence and commercial agriculture has developed to outpace population growth, with the production of major crops growing tremendously (ADB & FAO, 2015a). For instance, cereals such as maize have increased about four-fold in metric tons per area, vegetable production has expanded significantly into urban areas, and poultry and ruminants rearing have grown over the same period (ADB & FAO, 2015a).

The current agricultural economy in West Africa has evolved from predominantly production-level activity to more diversified activity, including off-farm work related to agriculture, such as agriculture services and manufacturing (Allen et al., 2018). In 2018, the regional employment record showed that agriculture and its related activities employ over 66% of the population. Even though primary production accounts for 78% of the employment in the sector and may differ per country, evidence shows that two-thirds of all the employment in West African countries are agriculture-related (Allen et al., 2018). Women play a significant role making up over 65% of the food economy in the sub-region and yet they do not have equal access and ownership to critical agriculture resources such as land in most places (Allen et al., 2018). Even though agricultural lands have increased with regional governments' investments and policies, productivity has been modest since 1980 compared to previous years, falling below the global production average (ADB & FAO, 2015a).

Together, these studies provide a sequence of historical events that have shaped the crop production system in West Africa. The evidence presented in these studies demonstrated that a section of scholars attribute the evolution of the earliest and later crop production system to environmental events, while others pointed to cultural, migration and economic events as drivers. Regardless of how the crop production system developed, these studies point to the complexities of biophysical and socioeconomic events guiding the transition from the earliest subsistence nature to a later livelihood activity. However, the missing pieces in these studies are how they failed to adequately acknowledge the implications of these complexities on localised crop production systems across West Africa. As these complexities evolve in the future, the need to understand the contextual characteristics of current cropping systems and the pathways to achieve sustainable cropping systems will be necessary for the survival of agriculture in West Africa.

2.4 Cropping systems in semi-arid West Africa and Northern Ghana

2.4.1 Conventional cropping systems in West Africa

Spatiotemporal arrangements and availability of water (rainfall) define most of the conventional cropping systems of West Africa (Blein et al., 2008; Masse et al., 2018; Schindler, 2009). These factors determine the type of crops to produce and whether the farming system will be a monoculture, mixed cropping or intercropping (Callo-Concha et al., 2012; Masse et al., 2018).

Spatially, the cropland location relative to the village or homestead of the farming household determines the type of cropping system practised (Callo-Concha et al., 2012; Schindler, 2009). Masse et al. (2018) observed that the spatial cropping system arrangement is in a "concentric ring" where the farming homestead or village is in the middle of the ring, and the cropping type changes as the ring expands with changing soil fertility levels. The cropland closest to the village is called village gardens or compound farms, with often fertile soils well-managed with animal droppings or compost (Callo-Concha et al., 2012; Masse et al., 2018). A village garden or compound farm is primarily a subsistence type of farming where monocropping of staple cereal crops occurs along with a few leguminous or vegetable crops (Masse et al., 2018; Zougmoré et al., 2014). Beyond the perimeters of village gardens are the bush fields or family lands belonging to the extended family (Masse et al., 2018). The cropping system on the bush or family land may be for subsistence or commercial purposes; thus, monocropping or mixed cropping, and the crop type(s) planted, may depend on household food security or financial needs (Blein et al., 2008; Masse et al., 2018). Grassland or forest plots are the croplands that belong to the entire community, and farmers can get access to these farmlands through the traditional authority of the community, commonly known as the "Tindana" in Northern Ghana (Callo-Concha et al., 2012; Masse et al., 2018; Schindler, 2009). Monoculture and mixed cropping are standard practices, and farmers may grow a mixture of leguminous or cereal crops for commercial purposes. For instance, the second most practised cropping system in Northern Ghana is the monoculture of groundnut or cereals (rice, millet or maize) often practised on family or community lands (Callo-Concha et al., 2012).

Temporally, a more permanent or continuous type of cropping is done in village gardens, while short fallow or long-fallow periods may occur on family or community lands (Callo-Concha et al., 2012; Masse et al., 2018; Schindler, 2009a). Applying manure, compost and household waste to village gardens makes it possible for farmers to practice continuous cropping (Callo-Concha et al., 2012; Masse et al., 2018). In semi-arid Ghana, continuous cropping of staple cereal crops intercropped with legumes is essential for household food security (Callo-Concha et al., 2012). Masse et al. (2018) found that the soil fertility levels on family and community lands are low, and farmers often practice short-fallow or long-fallows to help regenerate soil fertility. The monocropping of legumes and cereals between fallow periods helps restore soil nitrogen levels (Mason et al., 2015; Schindler, 2009). For instance, the cropping system adopted by farmers in semi-arid Northern Ghana and Burkina Faso is based on the soil types and water availability, especially in the short rainy season when monocropping of maize is practised on fertile compound land (Callo-Concha et al., 2012). At the same time, intercropping of cereals and legumes occurs on less fertile soils with limited water retention (Callo-Concha et al., 2012).

Rainfed agriculture is the dominant farming system in West Africa, and as such, some scholars argue that rainfall distribution is the primary determinant of the cropping system in the sub-region (Ouédraogo et al., 2017; Partey et al., 2018; Sultan & Gaetani, 2016; Zougmoré et al., 2016). Blein et al. (2008) categorised the West African cropping system into three groups based on rainfall distribution within the region's ecological zones: the humid, the semi-humid and the dry area agriculture systems. Rainfall in the humid areas is favourable for an all-year-round cropping system where root (cassava), tuber (yam, potatoes), and tree (oil palm, cocoa, plantain) crops dominate. More commercial agriculture happens in this area, especially with tree crops (Blein et al., 2008; Jalloh et al., 2012; Sultan & Gaetani, 2016a). The semi-humid area of West Africa is diverse, with relatively adequate rainfall to produce cereals (maize, sorghum), legumes (beans, groundnut), root crops (yam, cassava) and tree crops like cashew (Blein et al., 2008; Jalloh et al., 2012). The dry areas of West Africa, generally known as arid and semi-arid regions, are natural-resource limited environments that centre their agriculture system on efficiently managing limited resources like water, soils, and biodiversity to increase productivity (Blein et al., 2008; Padgham et al., 2015). However, the agriculture systems in arid and semi-arid areas rely on rain-fed agriculture characterised by limited rainfall to produce legumes (groundnuts) and cereals (millet, sorghum and maize), while irrigation options provide opportunities for cultivating rice and vegetables such as tomatoes and onions (Blein et al., 2008; Schindler, 2009). In the rainy season, farmers practice permanent mixed cropping of cereals and legumes on more fertile village gardens or compound farms, while in the dry season, farmers practice monocropping or mixed cropping on irrigated family or community lands near water sources such as riverside, dam or dugout (Callo-Concha et al., 2012; Schindler, 2009).

In the case of semi-arid Ghana, monocropping on compound land (farmland near homestead) is the most popular farming system where farmers grow staple cereal crops such as late millet, early millet, and maize combined with cowpea and okra (Callo-Concha et al., 2012). Except for rice production, which is often done on croplands with adequate irrigation water access, monocropping of other cereals such as maize, millet, and sorghum occurs on farmlands close to the farming household (Dakyaga et al., 2020; Schindler, 2009). Zougmoré et al. (2016) highlight that farmers rely on simple farm tools, including hoes and the occasional use of bullocks for land preparation due to the loose nature of the soils resulting from continuous cropping. Monocropping of legumes (often groundnut), cereal-legume intercropping (maize-groundnut) and mixed cropping of different legumes (often groundnut-cowpea mix) occur on distant family and community croplands because the drought-tolerant legumes, which require minimal supervision, are less attacked by pests, especially birds (Schindler, 2009). Cereal-legume intercropping, monocropping and mixed cropping of vegetables may also occur on croplands with access to irrigation. For instance, the monoculture practised in Northern Ghana, especially for tomatoes, often covers 60% of irrigated cropland use, while mixed cropping of tomatoes with onions or other vegetables covers 40% (Schindler, 2009). Due to the less fertile nature of distant croplands, smallholder farmers often intensify labour and inputs during land preparation through the crop cycle. Using tractors for ploughing and chemical fertilisers for soil improvement is a frequent practice for crop cultivation on distant farmlands (Dakyaga et al., 2020). Also, distant cropland with water access for irrigation can be a competitive space and expensive to cultivate due to the cost of resources, including machinery and labour costs (Schindler, 2009). Many scholars have observed that female household members often struggle to access these croplands, and when they do, it is expensive and labour-intensive to cultivate their preferred crops (Lawson et al., 2020; Nyantakyi-Frimpong, 2017; A. L. Wood et al., 2021). The summary of the characteristics of the conventional cropping systems in semi-arid Northern Ghana is presented in ***Table 1*** below.

Table 1: *Types of conventional cropping systems practised in semi-arid Ghana (Source: Researcher's compilation from literature).*

Cropping system	*Type*	Spatial	Temporal	Water demand	Crop type	Household needs
Monoculture	Monocropping of cereals	Village garden / compound farm	Continuous	Rainfed	Maize, early millet and late millet	Subsistence
	Monocropping of legumes	Community farmland	Short-term or long-term fallow	Rainfed	Groundnut, cowpea	Commercial
	Monocropping of rice	Community farmland along riverside	Continuous	Irrigated	Rice	Subsistence and commercial
	Monocropping of vegetables	Community farmland along the riverside	Continuous	Irrigated	Tomatoes, onions, pepper	Commercial
Intercropping system	Cereal-legume intercropping	Family/ community farmland	Continuous	Rainfed	Maize-groundnut/cowpea	Subsistence
Mixed cropping	Mixed cropping of cereals	Family farmlands	Short-term fallow	Rainfed	Sorghum and millet	Subsistence
	Mixed cropping of legumes	Community farmlands	Long term fallow	Rainfed or irrigated	Groundnut and beans	Commercial and subsistence
	Mixed cropping of vegetables	Community farmland along the riverside	Continuous	Irrigated	Tomatoes and onions	Commercial and subsistence
Crop rotation	Cereal-legume rotation	Community land	Continuous	Rainfed	Maize and groundnut	Commercial

Collectively, these studies highlight how water availability, soil fertility and household needs are critical to determining the type of cropping systems conventionally practised in West Africa. However, these studies did not emphasise how the rapidly changing biophysical and socioeconomic complexities may challenge conventional cropping systems across the region, particularly in Northern Ghana. Many studies have discussed how rainfall in West Africa has become more erratic due to the changing climate with implications for water security, soil degradation and biodiversity loss which may affect the sustainability of conventional cropping systems (Sultan & Gaetani, 2016; Zougmoré et al., 2016). In addition, high population growth and its related food demand are continuously affecting the length of the fallow period for soil nutrient restoration and exerting pressure on limited natural resources (ADB & FAO, 2015; Sarr, 2012). These biophysical and socioeconomic complexities make the conventional cropping systems in West Africa and Northern Ghana less desirable and force farmers to search for innovative options to lessen the impacts and sustain food production (Callo-Concha et al., 2012; Mason et al., 2015).

Nevertheless, these complexities are often localised and context-specific; understanding their implications on existing cropping systems could draw new insights to develop sustainable pathways to lessen their impacts. The next section reviews the sustainable pathways known in current literature to address the weaknesses of conventional cropping systems.

2.4.2 Sustainable cropping systems in semi-arid West Africa and Northern Ghana

The biophysical and socioeconomic challenges within West Africa's conventional cropping system have enabled different innovative approaches that help sustain the region's crop production (Sarr, 2012). These interventions and approaches target affected natural resources or human capacity that limit crop productivity. Climate-smart agriculture, agroforestry, conservation agriculture, precision farming and agroecology are various forms of sustainable agriculture designed to address a specific or combination of natural resource constraints (including climate change, soil degradation and loss of biodiversity) to sustain or increase productivity (Sarr, 2012; Zougmoré et al., 2014). Some of these sustainable systems also attempt to address socioeconomic constraints such as s access to resources and inequality that affect the agriculture system. Even though crop intensification/extensification has been criticised as unsustainable pathways, they are discussed for their role in increasing productivity. It is worth noting that these categories often have a lot in common and should not be considered completely distinct. **Table 2** below shows the strengths (pros) and weaknesses (cons) of sustainable cropping approaches in West Africa.

2.4.2.1 Climate-Smart Agriculture (CSA)

The impact of climate change on West Africa's agriculture without appropriate innovation or technology will affect food security in the region by reducing crop productivity substantially by 2050 (Sarr, 2012). The late onset of rainfall and shortening of the growing season due to climate change will require adaptation strategies that make the farming systems in semi-arid West Africa more robust (Blein et al., 2008; Sarr, 2012; Sultan & Gaetani, 2016). The adaptation strategies need to include water, soil, biodiversity, and crop management technologies, which are essential to increasing crop productivity by 2050 (Sarr, 2012; Sultan & Gaetani, 2016). CSA is broadly defined by experts as "*agriculture that sustainably increases productivity, enhances resilience, reduces greenhouse gases, and enhances achievement of national food security and development goals*" (Totin et al., 2018). CSA provides a good set of adaptation strategies for crop productivity and presents an opportunity for smallholder farmers in West Africa to enhance their adaptive capacity while supporting global mitigation efforts from the local level (Partey et al., 2018; Totin et al., 2018; Zougmoré et al., 2014, 2016). CSA strategies are applied contextually due to the differences in spatial impacts of climate change (Zougmoré et al., 2014, 2016). CSA's water and soil management strategies have been helpful in semi-arid West Africa, where drought occurrences, acidic soils, land degradation, and water stress lead to low productivity and incomes (Partey et al., 2018; Zougmoré et al., 2014).

There is substantial evidence to suggest that CSA practices such as improved crop varieties, water management techniques, agroforestry, increased soil organic matter, improved information services and fertiliser efficiency have the potential to increase food productivity and incomes for farmers in semi-arid West Africa (Partey et al., 2018; Zougmoré et al., 2016). Water management strategies such as irrigation farming (including water harvesting system), development of drought and heat-resistant crop varieties and implementation of water retention strategies (half-moon, Zai pits and stone bunds) enable farmers to adapt to water scarcity from the shortened growing season (Sarr, 2012; Zougmoré et al., 2014, 2016). For instance, Zougmoré et al. (2016), in their review of CSA practices in semi-arid areas of West Africa, found the following benefits; water harvesting and water conservation practices enabled profits for farmers up to 300 USD/ha; natural regeneration efforts resulted in an estimated annual gain of about 280 million USD from food, fuelwood and fodder production benefitting over 2.5 million people. In addition, zero tillage and the growing of cover crops help improve soil moisture and fertility, leading to high productivity (Mason et al., 2015; Partey et al., 2018; Zougmoré et al., 2014). In semi-arid Northern Ghana, CSA has encouraged information services that provide farmers with weather, market, and agriculture advisories (Zougmoré et al., 2016).

Even though CSA has been useful, Partey et al. (2018) criticise the promotion of agrochemicals like chemical fertiliser as part of the practice could harm soil and water resources. Non-governmental organisations (NGOs) and civil society organisations (CSO) have also criticised the corporate (multinational agribusiness) takeover of CSA for promoting modified inputs (like seeds) which may be expensive for smallholder producers (Alexander, 2019; Chandra et al., 2018). Also, CSA practice has gained much momentum with policy support from national and regional governing bodies in West Africa as an alternative to addressing the expected food crises under some climate change scenarios (Partey et al., 2018; Totin et al., 2018). However, challenges with implementing CSA in semi-arid West Africa, including financing, appropriate technologies, and clarity of the concept to smallholder farmers for practice, remain unresolved (Partey et al., 2018).

2.4.2.2 Precision farming

Crop management strategies to address soil and water constraints to increase crop productivity in semi-arid West Africa require strategic context-specific planning and implementation actions that take into consideration the variations within these constraints and design appropriate strategies that can effectively address them (Nyaga et al., 2021; Onyango et al., 2021). According to Aune et al. (2017), precision farming is the type of cropping system that provides context-specific strategies at the farm level to ensure the efficient use of inputs for crop productivity. Precision farming establishes a micro-environment for growing crops in dryer conditions (Aune et al., 2017b; OlubukolaOke & Aduramigba-Modupe, 2020). The initial step for precision farming is understanding the quality and quantity of the various natural resources base (especially water and soils) through the use of technology (sensors and Geographic Information systems – GIS) or local knowledge in the case of smallholder farmers (Onyango et al., 2021). For instance, geoinformatics technology can help identify land characteristics for suitable crops in dry regions for commercial farming, while smallholder farmers can use local knowledge to select suitable fields for growing specific crops (Onyango et al., 2021).

While some authors emphasise land management for precision farming, others focus on the systematic input selection under conditions suitable for crop varieties at a given time. Ideally, mechanised tools/technology in precision farming are necessary for applying correct doses of agrochemicals (fertilisers and pesticides), applying uniformity in crop spacing during planting, for seed priming and irrigation management (Aune et al., 2017; Gassner et al., 2013; OlubukolaOke & Aduramigba-Modupe, 2020). For instance, Aune et al. (2017) found that seed priming (selection and treatment) increases production by 20 – 30% when done correctly. Precision agriculture provides the necessary conditions for crops to grow in harsh conditions like semi-arid regions, as attention is given to the type of seeds to select, the amount of water to use and soil nutrients required for a particular crop variety (Aune et al., 2017; Gassner et al., 2013; Onyango et al., 2021). The precision agriculture system has the potential to enable sustainable intensification in semi-arid West Africa (Aune et al., 2017). Critics have argued that implementing precision agriculture in its purest form is expensive, technical, and therefore challenging for smallholder farmers to practice in West Africa (Onyango et al., 2021). However, some scholars have maintained that farmers could implement low-cost soil and water management strategies, including Zai pits, half-moon, and stone bunds, to increase and sustain productivity (OlubukolaOke & Aduramigba-Modupe, 2020; Onyango et al., 2021; Zougmoré et al., 2014)

2.4.2.3 Agroforestry

Agroforestry as a cropping system is described as integrating shrubs or trees with crops to improve the soil nutrient cycle, reduce land degradation and promote climate change mitigation (Zougmoré et al., 2016). Some scholars promote agroforestry as a means of rehabilitating degraded or diminishing forest/shrubland cover and, at the same time, improving soil nutrients, water and biodiversity for higher productivity in semi-arid West Africa (Félix, Diedhiou, et al., 2018; Félix, Scholberg, et al., 2018). Management of different crop species at the farm level, especially cereals and legumes, allows for maximising the use of inputs (nutrients, biomass and water) at the root level and provides opportunities to reduce total crop failure (Félix, Diedhiou, et al., 2018). Evidence shows that in semi-arid West Africa, woody and shrub perennials enable crops to do better by providing the needed biomass to conserve soil moisture and enhance soil nutrients (Félix, Diedhiou, et al., 2018; Mason et al., 2015; Masse et al., 2018). For instance, evidence shows increased soil carbon (20 to 70%) through heavy organic matter contents from litter and tree sediments. Also, soil nutrients, primarily nitrogen (N) and phosphorus (P) increased significantly (about 38% to 51%) under woody perennials than in areas without agroforestry (Félix, Scholberg, et al., 2018). Some agroforestry areas in the region have shown that woody perennials increase water content in soils (up to about 30%) more than other crop systems (Félix, Scholberg, et al., 2018).

Furthermore, crops have significantly improved under abandoned termite nests in agroforestry systems than in open fields. Termite nests develop in moist soils in woody areas and are rich in soil nutrients (calcium, nitrogen and potassium) essential for high productivity (Félix, Diedhiou, et al., 2018; Mason et al., 2015). Likewise, soil organisms' activities (like termites) promote nutrient recycling and improve soil structure, moisture, and formation (Félix, Scholberg, et al., 2018). The surrounding biodiversity, especially wild trees and shrubs, provide alternative nutritional diversity for farming households. The contribution of biodiversity to diet is more critical during food shortages and becomes an additional diet option during periods of food abundance (Félix, Diedhiou, et al., 2018). Overall, agroforestry in semi-arid areas can improve crop productivity by up to 100% compared to open field productivity (Félix, Scholberg, et al., 2018; Partey et al., 2018; Zougmoré et al., 2016). For instance, crop yields under the agroforestry system in the Northern parts of the region had 391 kg/ha grains higher than production on open fields (Félix, Scholberg, et al., 2018; Zougmoré et al., 2016). Even though policymakers in West Africa are keen on agroforestry as a sustainable farming option to balance productivity and tree/shrubs management, smallholder farmers are more interested in increasing productivity which affects the implementation of the farming system (Partey et al., 2018).

2.4.2.4 Conservation agriculture (CA)

Mason et al. (2015) argue that conservation agriculture as a farming system can increase soil nutrients and moisture, restore degraded soils, increase species diversity, and reduce greenhouse gas emissions caused by traditional forms of farming in West Africa. CA aims to increase crop productivity with limited disturbance to the soils. CA is achieved through minimal/zero tillage by increasing cover crops and crop residue on the field as mulch (during fallow) and rotating cereals with legumes or trees (Mason et al., 2015; Onyango et al., 2021). Also, crop residue can be increased with increasing crop productivity while intensifying soil and water management practices such as zero tillage, stone bunds and Zai pits (Mason et al., 2015; Partey et al., 2018; Zougmoré et al., 2016). Mason et al. (2015) have criticised how CA is practised in semi-arid West Africa as lacking the trade-offs between using crop residue as mulch or fodder or household energy use. Innovative fodder sources for livestock (including establishing grazing fields) and household energy use, including solar-powered systems for electricity and gas for cooking, may be required in conservation agriculture (Mason et al., 2015). They further argue that CA could increase pest and invasive species that could affect crop productivity. Weed and pest control in conservation agriculture will require the efficient application of cost-effective agrochemicals as a complementary practice to conservation practices (Mason et al., 2015).

2.4.2.5 Agroecology

Agroecology centres on reengineering the agriculture systems by restoring and maintaining biophysical properties damaged by climate change or human activities (Adenle et al., 2019; Masse et al., 2018). Ecological intensification seeks to increase crop productivity by improving ecosystem services. This farming system improves biodiversity, enhances organic matter and nutrient cycling, provides solutions for water scarcity, and manages semi-arid landscapes for high productivity (Masse et al., 2018). Biodiversity practices such as introducing essential micro-organisms (nitrogen-fixing bacteria) into soils and growing crop species that function together (legumes and cereals) can enhance plant growth and increase productivity (Félix, Scholberg, et al., 2018; Mason et al., 2015). Through tree planting and natural regeneration, agroforestry practice within the ecological intensification system improves biodiversity and the soil nutrient cycle, prevents soil erosion, and increases soil organic matter content (Aune et al., 2017; Félix, Scholberg, et al., 2018; Masse et al., 2018).

However, some authors, like Masse et al. (2018), argue that agroecology needs to be broader than its current definition to include crop-livestock integration, where crop residue serves as fodder, and dropping from livestock provides organic manure for crop production. He further claims that agroecology's central focus must be using available natural resources to enhance the cropping system. For instance, pest control through crop species variety and the introduction of natural enemies within uncultivated fields could provide alternative pest control strategies than pesticides, which can long-term impact biodiversity (Masse et al., 2018). Other studies support Masse et al. (2018) stands on agroecology with emphasise on practicing sustainable water management techniques (Zai pits and half-moon techniques), drought-resistant crop types, and household wastewater for compound gardens (Masse et al., 2018; Partey et al., 2018; Zougmoré et al., 2014). These studies do not provide adequate evidence on estimated productivity and economic outcomes to support the usefulness of practicing agroecology in West Africa.

2.4.2.6 Intensification/extensification

Unlike the other production systems discussed earlier, agriculture intensification and extensification may not necessarily be sustainable approaches but a farming system to increase productivity. Regional studies show that as the population grows at 2.5% annually in West Africa, coupled with the biophysical constraints, expanding the land area and increasing inputs for higher productivity have become necessary for smallholder farmers (ADB & FAO, 2015a; Wiebe et al., 2017). Wiebe et al. (2017) tracked the growth of agriculture in Sub-saharan Africa for nearly half a century (1961 -2014); they discovered that area expansion had been estimated to contribute to an increase in productivity of 60%, while input intensification contributed to about 40% of the total productivity growth, especially in West Africa. In some parts of semi-arid West Africa, including Ghana, due to low technology and access to resources, over 80% of the recorded increase in staple crop production has been achieved through area expansion rather than input or yield enhancement (Callo-Concha et al., 2012). Extensification and intensification for cereal productivity in West Africa contrast with the strategy used for crop productivity in developed countries, where almost all increases in cereal production came from crop enhancement, rather than area expansion or input intensification (Wiebe et al., 2017).

However, expanding cultivated area to increase crop productivity can negatively affect biodiversity and increase land degradation (especially erosion) as natural areas, especially forests, are converted to cropland (ADB & FAO, 2015; Wiebe et al., 2017). Continuous input intensification can affect agricultural water and soil quality, increase runoff, damage biodiversity and increase greenhouse emissions (Wiebe et al., 2017). Even though most scholars have agreed that intensification and extensification have environmental costs, Namara et al. (2011) insist that in semi-arid Northern Ghana, both extensfication and intensification are necessary for increasing the potential of arable lands, primarily through irrigation, to expand the food economy.

Table 2 below shows the positives (pros) and negative (cons) implications of the different sustainable farming systems practiced in semi-arid West Africa including Northern Ghana.

Table 2: *The implications of sustainable agriculture systems for smallholder farmers in semi-arid Northern Ghana (Source: researcher's compilation from literature).*

Sustainable Agriculture	Implications for smallholder farmers	
	Pros	**Cons**
Climate-smart Agriculture	• Improved crop varieties • Water conservation (half-moon, Zai pits and stone bond) • Soil conservation (zero tillage, compost use, increased cover crops) • Use of irrigation through water harvesting • Agroforestry (natural regeneration and growing of tree crops) • Access to information (including weather, markets, and agronomic practices) • CSA concept has been widely accepted in policy	• It can be expensive to implement • Lack of clarity for the CSA concept for smallholder farmers • Inadequate emphasis on socioeconomic drivers • Lack of well-defined appropriate technology
Agroforestry	• Efficient management of different crops and tree/shrub species • Soil and water conservation through biomass from tree litter and cover crops like cowpea • Promote soil organisms the improve soil structure and nutrients • Source of ecosystem services (extra dietary needs) for farming household • Promotes mitigation efforts through increased carbon stock	• Tree and shrub management may not be a priority for smallholder farmers • Lack of socioeconomic considerations in the concept • Risk of soil nutrient and water competition from trees and invasives species • Labour-intensive to manage crops and tree species
Conservation agriculture	• Improves soil and water conservation through increased cover crops with legumes, zero tillage and crop residue on the field • Species diversity through intercropping improves soil Nitrogen and Carbon • Cover crops ad crop reduces runoffs and maintains nutrient-rich topsoil • Reduces greenhouse gas emissions caused by agriculture	• Competing use of crop residue as fodder for livestock than soil cover • Weeds can be difficult to control • High risk of invasive species • Labour intensive • Access to land for fallow may be difficult, especially for women farmers
Precision agriculture	• Efficient use of water and soil inputs such as chemical fertiliser application and irrigation • The concentration of strategies at the farm level improves productivity • Local knowledge can be used in precision agriculture to manage soil and water resources • Micro dosing of agrochemicals reduces environmental pollution and greenhouse gas emissions from agriculture	• Precision farming can be expensive to practice • Practices can be technical for smallholder farmers • Labour-intensive to manage the crop, water and soil resources • Concentration on improving only productivity at the farm level may not reflect on the overall improvement of the food system
Crop Intensification/ extensification	• Improved crop varieties and agrochemical use significantly improve productivity in the short-term • Increased productivity through increased soil and water inputs • Land expansion can increase the potential of unexplored lands for agriculture • The most convenient way to improve crop productivity for smallholder farmers	• Land expansion can be damaging to biodiversity • Water and soil quality are at risk of damage through chemical pollution and erosion • Increased greenhouse gas emissions with unchecked chemical use and land expansion • Expected long-term impact on the food production system as natural resources may not be able to support crop productivity • Labour intensive
Agroecology	• Restores and maintains damaged water, soil and biodiversity resources • Soil and water conservation through cover crops and increased organic matter content • Tree planting and natural regeneration improve the ecosystem services for farming households • Promotes mitigation efforts through forest management • Crop-livestock integration can increase organic manure for soil improvement	• Labour intensive • Competing use of crop residue as fodder for livestock than soil cover • Weeds and pests can be difficult to control • High risk of invasive species

Overall, the studies reviewed in this section highlight that sustainable agriculture systems in West Africa are aimed at sustaining productivity and agriculture livelihoods for farmers without any environmental cost. As described in the literature, the basic characteristics of these cropping systems show that sustainable agriculture is an evolving concept where earlier concepts influence later concepts based on emerging challenges. For instance, agroforestry and conservation farming became the building blocks for developing CSA to address the impacts of climate change on agriculture (Partey et al., 2018). As much as sustainable farming systems are gaining ground in policy and scholarly circles in West Africa, they largely remain conceptual than practical for farmers. Callo-Concha et al. (2012) acknowledged that farmers are more concerned about immediate productivity increases than future sustainability due to increasing food demand, as such intensification and extensification are common systems. Farmers may show little interest in sustainable systems, possibly due to the radical introduction of these new farming concepts for practice than their gradual integration into conventional/existing farming systems. However, this radical approach to introducing new farming concepts to farmers remains one of the critical inadequacies yet to be addressed within the current sustainable agriculture literature.

Furthermore, a common limitation of how these sustainable farming systems are described is that they focus more on addressing the direct biophysical risks to agriculture and less on the socioeconomic and institutional threats that could hinder crop productivity and sustainability of the cropping system. NGOs and CSOs have criticised proponents of sustainable cropping systems like CSA for neglecting social equity/justice issues in their conceptual framing (Alexander, 2019; Chandra et al., 2018). Nyantakyi-Frimpong (2017) strongly argues that in Northern Ghana, where cultural norms deepen gender/social inequality, inequitable access to resources (inputs and services) negatively impacts efforts to achieve a sustainable cropping system. The SI framework adopted for this study builds upon existing cropping systems (conventional or sustainable) and addresses the socioeconomic limitations in current sustainable agriculture concepts.

2.5 Sustainable intensification (SI) of agriculture systems

Amidst rapid environmental and socioeconomic complexities, several studies (Campbell et al., 2014; Garnett et al., 2012; Musumba et al., 2017) including recommendations from the IPCC (2022) proposes SI as a critical pathway to meet future food demand sustainably. Musumba et al. (2017) describe SI as a production system in which agricultural resources are optimised efficiently to increase production without land expansion, avoid adverse environmental impact, and build natural and socioeconomic capital. As agriculture sustainability concepts evolve, Campbell et al. (2014) emphasise that sustainable cropping systems like CSA must embrace the key principles of SI, where efficiency is required, and environmental and socioeconomic goals are both priorities. The first exploration of the SI concept was in the 1990s within Africa's crop production systems, where increasing yields and reducing environmental degradation were the main concerns (Garnett et al., 2012; Musumba et al., 2017). Over the years, the concept has evolved from focusing on productivity and reducing environmental impact to a broader framework for achieving social, economic and institutional outcomes within agriculture production systems (Musumba et al., 2017). Authors like Fischer et al. (2020) have strongly argued for the inclusion of gender equity in SI concepts, especially in areas where cultural norms limit women's access to croplands. However, their argument is inadequate as social inequity may go beyond gender to education and age based on the context.

Furthermore, according to Garnett et al. (2012), the SI concept does not necessarily describe a particular agriculture system but is an aspiration of how food production systems should be framed to meet anticipated food demand. In a different argument, Robinson et al. (2015) imply that specific agriculture innovations (related to fertilisation, improved seeds and irrigation) may be required to balance productivity with improving natural capital with zero social cost, especially for dry regions in developing countries already disadvantaged in natural and socioeconomic resources. Garnett et al. (2012) further argued that an increase in productivity is not necessarily tied to a standardised global or regional output but to a specific output defined by agrarian communities to meet their food security and livelihood goals. This concept allows producers within the agriculture system to produce the quantity of food they "need" rather than what they "want", leading to reduced over-exploitation of environmental and socioeconomic capitals.

On the other hand, specific regional food production output is needed in Sub-Saharan Africa, especially West Africa, to meet the growing population and other biophysical and socioeconomic challenges that may hinder productivity (van Loon et al., 2019). For instance, in the case of Northern Ghana, the average population growth rate from 2011 to 2021 was about 2.9%, higher than the national average of 2.1%, and outpaced the agriculture growth rate, which was reduced by 5.4% during the same period (GSS, 2021). The increasing population combined with biophysical risks such as erratic rainfall further triggers rural-urban migration, draining active agriculture labour, especially from Northern Ghana to cities in the South, deepening the threat to agriculture sustainability for millions of people in the region (Ahmed et al., 2016). In addition, the weak governance structure or the inadequate institutional support from the national level to promote agriculture at the local level complicates existing challenges to sustaining agriculture in semi-arid Ghana (Padgham et al., 2015).

A few SI studies (Dakyaga et al., 2020; Hoeschle-Zeledon, 2021; Kotu et al., 2017) conducted in Northern Ghana attempted to address these challenges to increase productivity by implementing a set of interventions/technologies and assessing their effects on crop production. For instance, Kotu et al. (2017) assessed sustainable intensification practices (SIPs), including cereal-legume systems, fertiliser application, conservation practices and improved seeds, and found that combining these practices significantly increased crop yields. Similarly, Dakyaga et al. (2020) used crop-livestock and land management interventions among farmers in Northern Ghana and discovered that these interventions enabled farmers to increase yields. However, an issue with intervention-oriented research is that the outcomes may be exaggerated or biased in favour of the interventions and diminish existing/local knowledge that may be essential for sustainable farming. Robinson et al. (2015) argue that SI is not necessarily a trade-off between an intervention (intensification) and local knowledge but an opportunity to understand existing farming systems' characteristics to make them sustainable. Similarly, in a review of about 40 SI-related projects in 20 SSA countries, Pretty et al. (2011) concluded that there is no blueprint for SI and that implementing SI will require negotiating the existing cropping systems with interventions. Another limitation of SI intervention projects is that it may be hard to distinguish from other sustainable farming systems if the focus is only on achieving on-farm outcomes and not an integrated approach to achieving both on-farm and off-farm outcomes as indicators of the overall sustainability of the agriculture system (Campbell et al., 2014).

Overall, the studies presented in this section indicate that SI is an evolving concept that embraces critical socioeconomic issues often neglected in earlier agriculture discussions. It is, however, inconclusive whether the concept should be a set of interventions or guiding principles for how different existing agriculture systems should look. Despite these controversies, SI as an intervention or a guiding principle may not be possible if researchers do not understand the food production system's underlying biophysical, socioeconomic and institutional characteristics. The present study argues that understanding these characteristics will help resolve these controversies by providing reasons for productivity differences in semi-arid Northern Ghana and delivering the fundamentals (barriers and entry points) for SI as a guiding principle and intervention in the region. The next section discusses the characteristics of the crop production system in Northern Ghana, as found in previous studies.

2.5.1 Biophysical characteristics of the crop production system in semi-arid West Africa/Northern Ghana

The risk from biophysical factors, and their management, are relevant for contextualising SI in West Africa and Northern Ghana. Previous studies highlight four main biophysical categories characterising the crop production system in the region. These characteristics include climate/water-related (rainfall, temperature, dry spells, irrigation and floods), edaphic/soil-related factors (soil nutrients, soil moisture, organic matter content, and soil erosion), ecosystem/biodiversity-related (forest and shrubs cover) and crop health-related (pest and disease). **Table 3** below summarises the critical characteristics of biophysical properties identified from the studies under review.

2.5.1.1 Climate/Water-related characteristics

i. Climate/water-related risks and impact on the crop production system

Crop production in West Africa is primarily through rain-fed systems with a bimodal regime in the South and unimodal regimes in the North (Blein et al., 2008; Jalloh et al., 2012). In semi-arid West Africa and Northern Ghana, yearly unimodal rainfall from April to September and a dry season period from November to March are experienced (Padgham et al., 2015). Historically, the climatic conditions in these areas have been characterised by drier conditions, especially in the wider West African Sahel since the 1980s, with erratic rainfall and high temperatures (Padgham et al., 2015). Even though in Northern Ghana, rainfall frequency and patterns over the past 30 years have experienced some dryness, the average rainfall over the entire country has increased over the same period (MFAN, 2018). On the other hand, annual mean temperature levels have increased for the past century between +0.4^{o}C to about +1^{o}C in Ghana, with most increases occurring in the North (Padgham et al., 2015). The combination of erratic rainfall and increased temperatures in West Africa has led to prolonged dry spells, droughts, and floods (Atanga & Tankpa, 2021; Marke, 2013; MFAN, 2018). For instance, in 2007, over 300,000 farmers in Northern Ghana suffered from prolonged and alternating drought and severe floods that disrupted crop production and other livelihood activities (MFAN, 2018). In addition, due to the unimodal rainfall regime and a single cropping season, semi-arid Northern Ghana experiences an average of 6-7 months of food shortages in a year compared to the south with bimodal rainfall and double cropping seasons (Atitsogbey et al., 2018; MFAN, 2018).

Future projections indicate that rainfall will decrease with increasing temperatures across West Africa, especially from March to June, reducing the length of farming (Padgham et al., 2015; Sultan & Gaetani, 2016). It is projected that in Northern Ghana, reduced rainfall and higher temperature events could reduce about 30% - 40% of water capacity in river basins and dams by 2050 (MFAN, 2018). Also, climatic events such as flooding and erratic rainfall could lead to post-harvest losses and increased pest occurrence, leading to crop failure across semi-arid West Africa (Jalloh et al., 2012; Sultan & Gaetani, 2016a). For instance, under future climate projections, erratic rainfall events will reduce household food crops like maize by about 15% in Northern Ghana (MFAN, 2018). However, Gariba and Amikuzun (2019) observed that even though low-lying areas may retain enough water for crop production, they are prone to flooding, while upland areas may suffer from drought from reduced rainfall, affecting crop productivity levels. Similarly, Niang et al. (2017) found that beyond climatic risks to water supply, the proximity of lowland areas closer to water tables makes them more suitable for crop production than upland areas further from groundwater tables.

ii. Climate/water-related risks management strategies

Several studies have shown that strategies to reduce climatic risks to the agriculture water supply may require both on-farm and off-farm strategies. The on-farm strategies proposed to manage water-related risks for crop productivity include water harvesting techniques (Zai pits and half-moon), improved seeds and irrigation (Marke, 2013; Partey et al., 2018; Zougmoré et al., 2014). Some scholars (Adenle et al., 2019; Partey et al., 2018) have argued that effective on-farm strategies to reduce climate/water-related risks must be easy to implement practices under sustainable farming systems such as organic farming, agroforestry and climate-smart agriculture. On the contrary, evidence in some parts of West Africa suggests that intensified systems with some technology for irrigated fields have more potential for higher productivity than rain-fed agriculture across all ecological zones (Crane et al., 2011; A. Niang et al., 2017; Worqlul et al., 2019).

However, an effective water management strategy will require combining technology-based strategies and sustainable management practices.

Moreover, Gariba and Amikuzuno (2019) identified that education, access to credit and extension services were beneficial for agriculture water security amidst harsh climatic risks as they enhance the capacity of farmers to practice water management strategies effectively. Similarly, Fagariba et al. (2018) found that access to weather information as an on-farm strategy in Northern Ghana enabled farmers to adequately plan for the farming season, reducing the impacts of climatic risks (erratic rainfall, increased temperature and dry spells).

2.5.1.2 Soil-related characteristics

i. Soil-related risks and impact on the crop production system

Soil sample studies from 14 West African countries showed that the region has older soils prone to nutrient leaching, especially in the arid and semi-arid areas (ADB & FAO, 2015). These soils vary across the region and support different crop types based on the ecological zone (Tanaka et al., 2017). Semi-arid areas of Northern Ghana have been reasonably suitable for cultivating household food crops, including cereals like maize, millet, sorghum and legumes (such as cowpea and groundnut) (Tetteh et al., 2016; Ziblim et al., 2012). Nevertheless, some authors discovered that these once-suitable soils had been degraded over the years with continuous cropping, slash-and-burn practices, short fallows, and deforestation, exposing the topsoils to nutrient depletion, soil moisture loss, and erosion (Biyogue, 2016; Boakye-Danquah et al., 2014; Tetteh et al., 2016). For instance, Biyogue (2016) demonstrated that soils in protected areas with limited human activities were better in soil organic carbon, phosphorus (P) and total N, micronutrients - Iron (Fe), Manganese (Mn), Zinc (Zn), and Copper (Cu), and exchangeable bases - Ca, Magnesium (Mg), K and Sodium (Na) than in cultivated areas. As the population grows, increasing food demand, anthropogenic activities were also found in similar studies to significantly reduce soil organic carbons relevant for crop production (Boakye-Danquah et al., 2014). On the contrary, Abubakari (2012) discovered that anthropogenic activities did not seriously impact soil chemical properties in savanna areas, even though longer fallows were slightly higher in N than in cultivated areas. This opposing finding could be due to different study areas, as densely populated areas could increase pressure on landuse that could impact soil properties.

Furthermore, Ziblim et al. (2012) established that soil physical properties in Northern Ghana, classified as Savannah Ochrosols, are generally shallow sandy loam topsoil, gravel-concentrated subsoils, and limited organic matter content, making them prone to rapid soil moisture loss and erosion. Rapid soil moisture loss and erosion have been worsened by erratic rainfall, poor management practices, and continuous cropping (Biyogue, 2016; Tesfahunegn et al., 2021; Tetteh et al., 2016). However, mixed soils, classified as Groundwater Laterite formed under wet tropical conditions due to intense weathering and groundwater leaching, located between alluvial soils within floodplains and uplands can potentially increase productivity, especially millet and sorghum (Crane et al., 2011). Even though other studies have shown the critical role of soil properties in crop production (Crane et al., 2011; Tanaka et al., 2013a), Tanaka et al. (2017) could not establish its role in higher productivity for semi-arid ecological zones.

Moreover, some scholars have found that the production of maize (the most relevant crop) in Northern Ghana was significantly reduced year on year due to degraded soils exacerbated by low soil moisture and without chemical fertiliser application (Tahiru et al., 2015; Ziblim et al., 2012). Similarly, Martey et al. (2013), in their study of maize growing fields across the region, concluded that the productivity of the crop was being affected as a result of the soils being less than required in low organic carbon (< 1.5%), total N (< 2%), exchangeable K (< 100ppm) and available P (< 10ppm, Bray 1). However, leguminous crops, including soybean, cowpea, and groundnut, performed better than cereals without any chemical fertiliser due to their ability to naturally enhance soils with total N fixation (Ziblim et al., 2012).

ii. Soil-related risks management strategies

Several studies have suggested that managing poor soils in semi-arid West Africa and across sub-Saharan Africa will require sustainable farming systems, such as CA and CSA (Joseph & Issahaku, 2015; Zougmoré et al., 2014). Typically, on-farm soil management practices such as longer fallows, zero tillage, cover cropping, crop rotation, stone bunding and intercropping are the CA/CSA techniques that significantly improve soil nutrients, reduce erosion and increase organic matter content for crop productivity (Joseph & Issahaku, 2015). However, limited knowledge exists on how these management strategies are practised across West Africa and Northern Ghana.

Some experts assert that the degraded nature of some soils in Northern Ghana will require intensive use of chemical fertiliser to restore their fertility (Boakye-Danquah et al., 2014; Martey et al., 2013; Tahiru et al., 2015). However, other scholars have questioned the sustainability of agrochemical intensification and argued that supporting traditional knowledge for soil management, such as manuring and composting, has better outcomes (Callo-Concha et al., 2012; Joseph & Issahaku, 2015). These debates on restoring degraded soils raise questions about the ideal or acceptable means of improving soil efficiency in semi-arid regions. Some studies have also emphasised that off-farm strategies that increase incomes could enable access to inputs and extension services, or strategies that promote participation in farmer groups could also increase farmers' access to chemical fertilisers and other on-farm management strategies for soil improvement (Martey et al., 2013; Tahiru et al., 2015; Tesfahunegn et al., 2021).

2.5.1.3 Ecosystem and crop health-related characteristics

i. Ecosystem and crop-health-related risks and impact on the crop production system

Ecosystem services from the forest are essential for food security and livelihood opportunities for the socioeconomic development of many rural households in West Africa (Boafo et al., 2016). However, the available forested areas in semi-arid West Africa, unlike the sub-humid/humid zones, are limited (with grassland and scrubs cover dominating) and are under continuous threat from anthropogenic activities in uncultivated areas (ADB & FAO, 2015a; Blein et al., 2008). Households rely on the ecosystem for subsistence and commercial activities, including charcoal production, logging, fuelwood harvesting, animal grazing, and agriculture expansion. For instance, Biyogue (2016) discovered that about 70% of Ghana's fuelwood and charcoal supply is obtained from the Northern and coastal areas, based on a limited forest resource base. The overexploitation of these ecosystem-based resources threatens the overall biodiversity balance that enables efficient and resilient water and soil properties within the crop production system (Biyogue, 2016; Boakye-Danquah et al., 2014; Joseph & Issahaku, 2015). Several studies have examples of how tree cover loss exposes topsoils and shallow water bodies to climatic events such as erratic rainfall, higher temperatures and dry spells, triggering excessive erosion and flooding (Biyogue, 2016; Tesfahunegn et al., 2021). Similarly, Boakye-Danquah et al. (2014) observed that the absence of tree cover in some Northern Ghana croplands reduced the amount of organic matter and biomass that could facilitate microbial activities to retain soil organic carbons, which, combined with organic manure and legumes, are essential for cereal production.

In addition to ecosystem risks, the Fall Armyworm (FAW) – *Spodoptera frugiperda* infestation has significantly threatened productivity in West Africa and sub-Saharan Africa, especially for maize production (Bariw et al., 2020; Koffi et al., 2021). Evidence shows that between 2016 and 2018, FAW infestation affected the productivity of maize in semi-arid production systems compared to other ecological zones in Ghana (Koffi et al., 2021). Bariw et al. (2020), in their work on crop health in Northern Ghana, observed that FAW infestation increases smallholder farmers' cost of production as they require more labour, time and agrochemicals to manage the pest outbreak, stretching the financial capacity to invest in soil and water management practices to increase productivity. Besides the FAW infestation, other notable pests associated with cereal production across the region include stem borers, grasshoppers, weevils and cutworms, while the common diseases include streak, smuts, rust and bacteria blight (Adu et al., 2014). Tanzubil (2016) also noted that legumes production in Northern Ghana, especially for groundnuts, is susceptible to root pests (white grubs, millipedes, symphilids, termites and wireworms) and leaf insects (sap-sucking aphids, whiteflies and leafhoppers), including leaf spot diseases.

ii. Ecosystem and crop-health risks management

Generally, most scholars agree that ecosystem management and pest/disease control require integrated efforts incorporating traditional knowledge systems and sustainable practices (Adu et al., 2014; Boafo et al., 2016; Tanzubil, 2016). Ecosystem management may apply agroforestry and conservation agriculture as sustainable pathways for creating a balance between agricultural land use and biodiversity maintenance (Biyogue, 2016; Boakye-Danquah et al., 2014). However, traditional knowledge systems such as customs, taboos, by-laws and sacred groves have protected natural resources from subsistence and commercial overexploitation (Boafo et al., 2016). Also, access to subsidised agrochemicals (pesticides and weedicides), increased extension services, and agriculture information services have proven in several studies to be helpful to farmers in controlling pests and diseases (Adu et al., 2014; Tanzubil, 2016).

Together, these studies describing biophysical characteristics debate whether the biophysical risks and related impacts are associated with the already limited natural resources in semi-arid regions or have been created by human activities. Some studies show that climatic conditions, especially rainfall and temperature, dictate the risks associated with water, soil and ecosystems, while others insist that human activities are to blame for these risks. Regardless of where each author stands on this debate, it was clear that as the population grows with increasing food demand, continuous human interaction with natural capital is inevitable, even though they may have implications for their sustainability. However, the pathways to reducing risks and improving natural capital have also been controversial among scholars. From the presented studies, the authors are divided on whether a management response should be through sustainable agriculture practices or intensified systems. Even though sustainable systems may be more rewarding in the long term than intensification, whether farmers can trade off one system for the other remained unanswered in these studies. The SI framework in the present study addressed these inadequacies in previous literature within specific case studies and individual farming households.

Table 3: *Summaries of biophysical risks, implications and management response of crop productivity in semi-arid Northern Ghana (Source: compiled from literature).*

	Risk factors	Implications	Response
Climatic/water	*Erratic rainfall, higher temperatures, dry spells and floods*	Food insecurity, an average of 6-7 months of food shortage, reduction in the length of the farming season and post-harvest losses	Water harvesting techniques (Zai pits and half-moon), improved seeds and irrigation, sustainable farming practices (organic farming, agroforestry and climate-smart agriculture) Education, access to credit and extension services and information delivery
Soils	*Degraded soil nutrients, low soil moisture, poor organic matter content and prevalent soil erosion*	Low organic carbon (< 1.5%), total N (< 2%), exchangeable K (< 100ppm) and available P (< 10ppm, Bray 1) are less than required for cereal production leading to low yields and food insecurity	Conservation agriculture techniques (longer fallows, zero tillage, cover cropping, crop rotation, stone bunding and intercropping), composting, manuring and chemical fertiliser use. Loans and credit (to access inputs and extension services) and FBO participation
Ecosystem	*Bushfires and deforestation*	Threatens the overall ecosystem and biodiversity balance to enable efficient and resilient water and soil properties that support crop production	Agroforestry and conservation agriculture create a balance between landuse for agriculture and biodiversity maintenance Traditional techniques (customs, taboos, by-laws and sacred grooves) to prevent overexploitation
Crop health	*Pest and disease*	FAW infestation increases the cost of production as they require more labour, time and agrochemicals to manage the pest outbreak, stretching the financial capacity to invest in soil and water management practices to increase productivity	Access to subsidised agrochemicals (pesticides and weedicides), increased extension services, and agriculture information

2.5.2 Socioeconomic characteristics of the crop production system in semi-arid West Africa and Northern Ghana

Beyond the biophysical characteristics of the crop production system, the socioeconomic settings within which a cropping system functions have the potential to enhance or hinder crop production.

As seen in the literature, socioeconomic characteristics of the crop production system include; *i)* Farmers' demographic characteristics, *ii)* Household production need, *iii)* Landuse and land tenure, *iv*) Access to agriculture resources, and *v)* Off-farm activities and incomes. **Table 4** below summarises the critical characteristics of biophysical properties identified from the studies under review.

2.5.2.1 Farmers' demographic characteristics in crop production

Some studies (Fallah-Alipour et al., 2018) argue that the agriculture system is a social construct; as such, farmers' or the farming household demographic characteristics are essential determinants of crop productivity within the agriculture system. Household characteristics, including household leadership, size and assets and individual farmer's gender, age, educational status and farm size, have implications for crop productivity in West Africa and sub-Saharan Africa (Amegnaglo, 2018; Boansi et al., 2017; Lawson et al., 2019; Ouédraogo et al., 2017; Oyekale, 2015; Theriault et al., 2017). Evidence shows that household and farmer characteristics impact perceptions of biophysical and socioeconomic risks, including the on-farm and off-farm strategies employed to cope with these risks (Dakyaga et al., 2020a; Lolig et al., 2014).

Several scholars have identified household leadership (household head) and size as determinants of managing water, soil, and other ecosystem properties. For instance, Gariba and Amikuzuno (2019) discovered that households in Northern Ghana with fewer members could manage water stress better through irrigation than those in larger households who may struggle to obtain the needed financial resources to practice irrigation due to competing household financial needs. Even though large households may be financially stressed to practice some strategies, they have the labour to expand cropland (Koffi et al., 2021). Similarly, the household head's age, gender, and education/literacy were critical determinants in adopting soil management practices to improve degraded soils (Lolig et al., 2014; Martey et al., 2014; Tesfahunegn et al., 2021). Tesfahunegn et al. (2021) established that soils in Northern Ghana are generally perceived as degraded regardless of the household type. However, much earlier work by Martey et al. (2013) found that male-headed households practice more fertiliser than female-headed households due to their higher-income levels from diverse livelihood activities.

Furthermore, older, educated farmers with bigger farm sizes are more likely to perceive biophysical risks negatively due to their experiences/knowledge and can adopt efficient strategies that reduce risk impact. For instance, in an ecosystem study, researchers discovered that elderly farmers were more knowledgeable about their ecosystems and took more practical steps to maintain them than younger farmers, known to exploit ecosystem services (Boafo et al., 2016). However, , Koffi et al. (2021) insist that younger farmers have more energy to invest in labour-intensive practices to control on-farm pest (FAW and birds) infestation than older farmers.

A farmer's gender, marital status, assets (radio, television and machinery), and culture can also determine access to social and economic opportunities that could enable higher crop productivity. Social differentiation studies have shown that male farmers usually have more access to credit, arable lands and extension services than female farmers and, as such are more likely to adopt yield-enhancing, crop-protecting or soil-restoring strategies than female farmers (Amegnaglo, 2018; Lawson et al., 2019; Theriault et al., 2017). Further evidence shows that female farmers' land tenure insecurity (motivated by cultural norms) in some communities has become a disincentive for investing in improving on-farm practices (Akugre, 2019; Nyantakyi-Frimpong, 2017; Tesfahunegn et al., 2021). However, female members of farming households dominate the off-farm livelihood activities as they seek alternative sources of income besides farming (Anang et al., 2020; Anang & Yeboah, 2019; Mccarthy & Sun, 2009). Regardless of gender, educated farmers are more active in non-farm income-generating activities than less-educated farmers whose livelihoods are centred around on-farm and migration activities (Marchetta, 2013).

2.5.2.2 Household crop production need

Generally, crop production across West Africa and SSA is predominantly for subsistence use, but also farmers take the excess production to the market (Mzyece, 2021). However, not all crops are for subsistence use, as some are mainly cultivated for commercial purposes (Dakyaga et al., 2020; Mzyece, 2021; Salifu, 2016). In Northern Ghana, farmers generally cultivate cereals and legumes for household food security and cash flow, respectively (Dakyaga et al., 2020a; Marke, 2013). Cereals such as maize, millet, rice and sorghum are the most relevant household food crops, while legumes such as soya bean and groundnut remain important commercial crops (Marke, 2013; Salifu, 2016). Even though cereals like maize are often produced for household consumption, due to their profitability and demand across the country, it remains the most relevant food crop for both food security and cash flows in Northern Ghana (McCartney et al., 2012; Mzyece, 2021).

Furthermore, where access to water is possible, farmers also grow vegetables (tomatoes, onions, peppers, and okra) in the dry season for commercial purposes and maize for consumption, even though this may be limited to smallholder farmers closer to water sources (Mzyece, 2021; Schindler, 2009). Farmers practising dry season irrigation or cultivating crops for commercial purposes are mostly part of well-organised FBOs who often take longer to market their produce through market aggregators, while subsistence farmers who cultivate through rainfed may sell less but faster on the open market (Namara et al., 2011).

2.5.2.3 Factors affecting landuse and land tenure

Access, control and use of the croplands are the essential characteristics of land use across West Africa and Northern Ghana. According to Musumba et al. (2017), access to cropland is the most critical factor in crop productivity in smallholder systems in the region. Smallholder farmers increase crop productivity by expanding farmland size, especially in uncultivated areas (Boakye-Danquah et al., 2014; MOFA, 2017). However, the growing population has constrained access to cropland, where land sizes are fragmented among household members, making it difficult to increase productivity. Ehiakpor et al. (2021) identified that farm sizes were relevant in adopting farm practices and new technology that leads to higher productivity in Northern Ghana. Farmers' access to cropland often depends on the ownership and control of these lands (Ahmed et al., 2016; FAO, 2014; Schindler, 2009). According to Schindler (2009), two types of farmland ownership are identified in Northern Ghana, namely community and family farmlands. Community farmlands are often distant farmland further away from the home dwellings and belong to the entire community but are overseen by the community chief priest (spiritual leader) or landlords called the Tindanaas (Schindler, 2009). Several studies have found that community lands can be accessed with permission from Tindaanas, and farmers can develop as much as they can, even though the lands are often challenging to cultivate because they are virgin land (Callo-Concha et al., 2012; Masse et al., 2018; Schindler, 2009).

Family lands are often closer to the homestead and belong to farming households (Schindler, 2009). At the household level, the access, control and size of cropland depends on gender, as women are not allowed to own lands but can access a portion from their husbands or family (Lawson et al., 2020; Nyantakyi-Frimpong, 2017). It is customary in most communities in Northern Ghana and some parts of West Africa that female household members cannot own property due to the strong patrilinear culture (Akugre, 2019). The lack of ownership and control over farmlands at the community and household level increases land tenure insecurity, especially for some social groups (women and migrants), prevents potential long-term investments into developing croplands with efficient management practices that enhance the biophysical properties for higher crop productivity (ADB & FAO, 2015; Akugre, 2019; Schindler, 2009).

Also, the farming system practised determines the land use type (Schindler, 2009). In the rainy season, farmers use family lands to practice mixed cropping while using community lands as fallow for crop rotation (Callo-Concha et al., 2012; Schindler, 2009). Farmers use croplands around water sources, including rivers, dams and dugouts, to practice dry-season irrigation (Schindler, 2009). However, land use around water sources for dry-season farming is often competitive and sometimes leads to conflict among users, especially between livestock herders and crop farmers (ADB & FAO, 2015a).

2.5.2.4 Access to agriculture resources for crop production

i. Agriculture inputs

Even though some farmers may have more access, control, and use of croplands than others, it requires adequate access to agricultural inputs to develop them for crop productivity. Access to agriculture inputs like seeds, fertiliser, and technology has been found in several studies to increase crop yields and farmers' adaptive capacity, especially in the face of increasing climatic risks (Amegnaglo, 2018). In semi-arid Northern Ghana, access to agriculture inputs such as fertilisers, improved seeds and agrochemicals (pesticides and weedicides) is provided through the government’s Planting for Food and Jobs (PFJ) programme or through direct purchase from input suppliers/retailers (Baanni, 2020; MOFA, 2017). The PFJ programme, which began in 2017, was implemented to modernise Ghana's agriculture by providing subsidised inputs, including fertilisers (organic and inorganic) and certified seeds (hybrid-maize, maize-OPV, rice, sorghum and millet) with responsive extension support (MOFA, 2017). However, despite its promising objectives, the PFJ programme has been criticised by several stakeholders for the frequently delayed supply and the cost of input transportation from city centres in the South to farming communities in Northern Ghana (Baanni, 2020; MOFA, 2017; PFAG, 2019). A review report of the PFJ programme indicated that about 90% of farmers in Northern Ghana experience a delayed supply of subsidised inputs (fertilisers and certified seeds), which often comes at a time when the planting cycle has already started (PFAG, 2019). According to Baanni (2020), the delayed input supply to farming communities occurs due to poor procurement arrangements between the government and input producers, affecting the supply chain from the PFJ secretariat at the national level to smallholder farmers at the local level.

Across West Africa, the constraints in demand and supply of subsidised inputs from government interventions create an opportunity for the private sector to take over the supply chain and provide the inputs directly to farmers when they are most needed (ADB & FAO, 2015a). Unfortunately, challenges with private input supply, such as high cost, poor quality, certification, and limited quantity, have hindered input suppliers' capacity to meet the demand for input supply and delivery at the local level (ADB & FAO, 2015a). An effective public-private partnership could resolve supply and cost challenges for farmers to access input on time for the cropping cycle.

ii. Agriculture Services

There is a linkage between the supply and delivery of inputs and agriculture services. However, agriculture services are generally poor across SSA and West Africa (Ziadat et al., 2015). Particularly in Ghana, input supply and delivery are done through local institutions such as the department of agriculture (DOA) and NGOs that provide extension services to farmers (Dakyaga et al., 2020a). These institutions provide services related to information, financing and technology transfer. However, in West Africa, limited human and financial capacity makes it difficult for these institutions to provide timely services to farmers (Sidibé et al., 2018). Access to accurate, reliable and timely information can increase farmers' adaptive capacity and enables them to make appropriate decisions that can enhance crop production levels (Oyekale, 2015; Partey et al., 2018). In a study conducted by Lolig et al. (2014) in the Upper West region of Ghana, they found that farmers with access to information such as weather forecast, planting date, and farming technologies were more likely to cope with droughts and floods as such enhancing their adaptive capacity. Access to agriculture extension services allows vulnerable farmers, predominantly female farmers, to access information that enables adopting new technologies and on-farm strategies (Donkor et al., 2016). However, access to these services depends on proximity, as Etwire et al. (2013) discovered that farmers in Northern Ghana who often receive services like technical and capacity training were those closer to extension services.

Furthermore, even though financial services for agriculture are limited across West Africa and in SSA, several studies have found increased yields for farmers who accessed credit compared to those without credit (Anang & Asante, 2020; Lolig et al., 2014). Farmers' access to capital, credit or any form of wealth increases their capacity to invest in technology and farming practices that enhance yields compared to farmers with less or no capital access (S. A. Wood et al., 2014). Investment in technology and on-farm practices can increase the smallholder agriculture system's resilience against biophysical risks (Amegnaglo, 2018; Partey et al., 2018; Rosenstock et al., 2018). Ehiakpor et al. (2021) demonstrated in their work in Northern Ghana that farmers' ability to access financial assistance, including credit and loans through formal and informal financial services, enabled them to adopt and intensify soil, water, and ecosystem practices that promote sustainable agriculture. Another study also found that credits and extension services were the most valuable incentives that encouraged farmers to try new farm technologies in Northern Ghana (Etwire et al., 2013). Generally, smallholder farmers with access to extension services often receive the relevant information to access credits to adopt new technologies that can improve water and soil properties for higher yields (Donkor et al., 2016; Ehiakpor et al., 2021; Lolig et al., 2014).

Furthermore, the Village Savings and Loans Associations (VSLAs) have been found by several studies to be valuable sources of financing that enable vulnerable groups to access small loans to purchase inputs like fertilizers and improved seeds and machinery like a tractor for their farms (Dakyaga et al., 2020a). Other scholars *have also* argued that cost-sharing financing schemes like subsidies than loan services with minimal interest are better ways of enabling smallholder farmers to adopt strategies and technologies that enhance resilience (Rosenstock et al., 2018).

However, the question remains if financial services for low-producing farmers could put some of them into debt as climate change affects yields and no effective crop insurance policy is available as security in Northern Ghana.

iii. Farmer groups/associations

Another noticeable characteristic of the agricultural system in West Africa is farmers' participation in formal or informal farmer groups (Dakyaga et al., 2020a; A. Salifu & Funk, 2012). Farmer groups are organised within farming communities for farmers to support each other with labour, agriculture resources (inputs and services), farm advisory and the general welfare of members (Namara et al., 2011; A. Salifu & Funk, 2012). In Northern Ghana, evidence from cereal production shows that farmers who participate in farmer groups are more likely to adopt efficient on-farm practices and have increased productivity than those who did not participate in any farmer group (Abdul-Rahaman & Abdulai, 2018; Addai et al., 2022; Martey et al., 2014; A. Salifu & Funk, 2012).

Efficient use of agriculture resources (technology and farm machinery) enabled by extension services has been facilitated through farmer groups across West Africa (Addai et al., 2022; Anang & Asante, 2020; A. Salifu & Funk, 2012). Even though farmer groups are critical for adopting technologies and increasing productivity, smallholder farmers' demographic characteristics (gender, age and household head), income, off-farm work and assets determine who can participate in farmer group activities (Addai et al., 2022; Martey et al., 2014). Several studies have concluded that the location (availability of innovation options and environmental/socioeconomic constraints of the area), marital status, and household size are related to access to resources and crop productivity in West Africa (Lawson et al., 2019; Ouédraogo et al., 2017; Oyekale, 2015). For instance, the willingness to participate in farmer groups to access inputs and services depends on the availability of these groups within their communities (Addai et al., 2022; Martey et al., 2014).

2.5.2.5 Off-farm income generating activities

Several authors claim that the declining crop yields due to climatic risks, especially in rainfed crop production systems, have forced farmers to diversify their livelihoods from farming to more off-farm activities (Anang et al., 2020; Kuwornu et al., 2018; Marke, 2013). However, Mccarthy and Sun (2009) suggest that the vulnerability of the crop production system to climatic risks was not always the primary reason smallholder farmers chose to partake in off-farm income-generating activities in some parts of Northern Ghana. As the rural economy develops, farmers may diversify their livelihood activities with new work opportunities, not necessarily because of declining yields. However, as climatic conditions worsen, farmers may have limited on-farm options to meet food demand and may have to partake in more off-farm options.

Anang et al. (2020) define off-farm work as "any activity undertaken by the farmer or farm household outside farming as an additional source of income." The typical off-farm work found in Northern Ghana includes activities related to farming, such as agro-processing, charcoal production, firewood collection, and non-farm work, including petty trading, migration (for work) and craftmanship (Anang et al., 2020; Marchetta, 2013; Marke, 2013). Several researchers have concluded that off-farm work is vital for farming households as it generates income for farm inputs and services to enhance crop productivity and has proven to alleviate poverty and hunger (Anang et al., 2020; Anang & Yeboah, 2019). Evidence from Northern Ghana shows that participation in off-farm work reduced rural poverty by 13% (Issahaku & Abdul-Rahaman, 2019) and increased smallholder farmers' investment in farming and incomes from the sale of crop yields (Anang et al., 2020; Mccarthy & Sun, 2009).

Off-farm incomes also enable smallholder households to access other nutritional foods, including fish, meat and vegetables, that may not be available to supplement the dominant staple cereal crops (Kuwornu et al., 2018; Zereyesus et al., 2017). Even though off-farm work may be helpful for income generation and food security, not all farming households have the capacity to participate or fully benefit from it. Evidence shows that poorer households may not have the resource capacity to engage in off-farm work considered more rewarding, such as petty trading and weaving, as wealthier farmers are more likely to engage in those activities (Marchetta, 2013; Mccarthy & Sun, 2009). However, Marchetta (2013) noted that poorer households without the resources to establish non-farm work often resort to seasonal migration for work in the cities as off-farm activity. Some authors argue that there is the possibility of establishing sustainable farming systems that ensure food security and alleviate poverty through a functioning nexus between on-farm work and off-farm activities for vulnerable groups in Northern Ghana (Issahaku & Abdul-Rahaman, 2019).

Table 4: *Summary of socioeconomic factors and implications for crop productivity in semi-arid Northern Ghana (Source: compiled from literature).*

Factors	Characteristics	Implications
Gender of household head	Male and female-headed households	Male-headed households are likely to access more resources to increase on-farm adoption than female-headed households due to their higher-income levels from diverse livelihood activities
Age	Elderly and youthful farmers	Older farmers have longer experiences interacting with biophysical and socioeconomic risks, which may influence their perceptions.
Education	Farmers with formal education and those without formal education	The higher a farmer's education, the more likely to participate in non-farm income-generating options than uneducated farmers who may depend on farm work and migration activities.
Location	Farmers' proximity to resources	The closeness of a farmer to agricultural resources could determine their access to natural, financial and social capital for productivity.
Asserts	Ownership of manufactured assets (machinery, communication devices and vehicle)	Ownership of assets such as mobile phones and radio increases farmers' ability to receive agricultural information
Landuse and land tenure	Cropland access, ownership and use	Land tenure insecurity (for women and migrants) prevents long-term investments in crop productivity
Input supply	Subsidised chemical fertilisers, improved seeds and agrochemicals	Delayed supply of subsidised fertilisers and certified seeds affects farmers planting cycles and may cost more to access them on time from private input suppliers
Farm services	Information, financing and technology transfer	Access to accurate, reliable and timely information, financing and technology increases adaptive capacity and enables appropriate decisions on farming
Farmer groups	Village savings and loans associations (VSLAs) and Farmer based organisations (FBOs)	Farmer groups support members with labour and agriculture resources (inputs and services) to increase yields and the general welfare
Financial resources	Credit, loans and personal savings	Access to capital, credit or any form of wealth increases investment and adoption of technology and farming practices that enhance yields
Household food needs	Commercial and subsistence crops	Cereals (maise, millet, rice and sorghum) are for consumption, while legumes (soya bean and groundnut) remain important commercial crops
Off-farm income generating activities	Agro-processing, charcoal production, firewood collection, petty trading, migration and craftsmanship	Off-farm work is vital for farming households as it generates income for crop productivity and has proven to alleviate poverty and hunger

Overall, this section points to the evidence supported by most studies that socioeconomic characteristics of the crop production system do not stand alone but interact with each other and biophysical characteristics to determine productivity. For instance, several studies established that farmer and farmer household biographic characteristics like gender, age, education, headship, size and location determine how other socioeconomic characteristics, including landuse, crop type, resources and off-farm activities, are perceived, accessed, adopted and used within the crop production system. However, the debate among most authors on this subject is the extent of impact characteristics will have on each other as they interact. For instance, experts have debated whether poor yields from climatic conditions are responsible for farmers seeking options in off-farm activities. Similarly, there are controversies on whether large household sizes enable or hinder participation in irrigation activities. These debates imply that the characteristics of the crop production system and how they affect production are diverse across Northern Ghana; as such case-study analysis could enable researchers to establish context-specific reasons for crop productivity.

Furthermore, socioeconomic characteristics and their implications on sustainable agriculture are insufficient in the current literature on crop production, as most studies focus on increasing yields. Similarly, some institutions (NGOs and CSOs) have criticised the inadequate discussion of equitable resource access (especially land) and the role of institutions in sustainable agriculture literature. Even though emerging SI studies included equity issues in their framework, little is known about their application in West Africa and Northern Ghana. The present study aimed to explore the importance of diverse socioeconomic factors as a potential enabler of SI. The next section focuses on institutional characteristics hindering or supporting higher productivity.

2.5.3 Institutional characteristics for agriculture innovation

Different authors describe institutions based on their functions. Institutions are defined from a social perspective as collective arrangements with common goals to serve a group of people (Tuomela, 2020). However, others have argued from a corporate lens that institutions must have a regulative and hierarchical structure that governs their activities (Guala & Hindriks, 2020). The present study considers institutions as non-profit or for-profit social arrangements with or without regulative structures representing a known group(s) of stakeholders directly tied to the governance of the agriculture system. The role of formal and informal, private and public institutions is considered essential to developing agriculture in West Africa and Northern Ghana. These institutions are related to financing, policy, operations and advocacy at the national and local levels (Yaro et al., 2015). Studies have shown that agriculture-related institutions are constrained by several factors that hinder the ability to implement innovative strategies that could enhance SI in semi-arid areas (Hounkonnou et al., 2012). However, institutions could also leverage opportunities or entry points to reduce constraints and advance agriculture productivity and SI goals.

2.5.3.1 Institutional constraints for agriculture productivity and innovation

i. Weak agriculture policies

Several countries in West Africa have implemented policy measures to boost agriculture productivity, as it continues to be a critical component of regional and national development (Hounkonnou et al., 2012; Sidibé et al., 2018; Totin et al., 2018). Since the 1990s, Ghana's agriculture sector has seen several specific and general policies geared toward enhancing productivity (Mawunyo & Woedem, 2013). See **Table 5** below. Specific agriculture policies are aimed at boosting investments, market participation, and mechanisation of the agriculture sector in Ghana. Even though these policies have been successful in enhancing agriculture to some extent, the changes in political power, especially in 2000, 2008 and 2016, have made them less effective. New governments often change policy direction or initiate overlapping policies affecting resource allocation for their implementation (Mawunyo & Woedem, 2013; World Bank, 2017). For instance, in 2017, the newly elected government committed resources to implement the PFJ policy alongside existing policies like the METASIP and FASDEP II initiated by the previous governments that served similar purposes (World Bank, 2017).

Change in agriculture policies affects government commitment to investment in existing programmes affecting resource distribution such as funding allocation for logistics, inputs and services. African governments' commitment in the Maputo and Malabo Declaration to invest about 10% of their public expenditure in agriculture has not been successful, especially in Ghana, where only up to 6% of the national budgetary allocation goes to agriculture (Hazel et al., 2019; MOFA, 2017). However, about 70% of the total agriculture budget is funded by donor partners, and over two-thirds of the sector’s allocation goes into export crops like cocoa production, leaving a significantly low budgetary allocation for non-export food crops like cereals (Hazel et al., 2019; World Bank, 2017). Benin (2019) criticised the overreliance on donor funding to execute agriculture policies and programmes and insisted that such a funding model makes their sustainability less likely.

Table 5: *Specific and generalised policy frameworks to boost agriculture in Ghana (Source: Compiled from literature).*

	Policy	Period	Aim
Agriculture development	*Medium-Term Agricultural Development Programme (MTADP)*	1990 - 2000	Promote institutional reforms required for increased investments and market-oriented agriculture growth, emphasising private sector participation in various segments of the agriculture value chain.
	Accelerated Agricultural Growth and Development Strategy (AAGDS)	2000 - 2010	To increase the sector's annual growth from 4% to 6% from 2001-2010 by prioritising irrigation, mechanisation, input delivery and promoting high-value crops.
	Food and Agriculture Sector Development Policy (FASDEP I)	2002	A guiding framework to implement agriculture sector objectives in the GPRS I policy, focusing on strengthening the private sector as the engine of growth.
	Food and Agriculture Sector Development Policy (FASDEP II)	2006	A framework to achieve longer-term policy agenda for the agriculture sector component of GPRS II.
	Agriculture Strategic Plan (ASP)	2003 - 2005	To resolve the weakness and threats within the GPRS, FASDEP and AAGDS policies.
	Medium-Term Agriculture Sector Investment Plan (METASIP)	2011 - 2020	A medium-term policy framework to achieve agriculture modernisation is outlined in the GSGDA policy to achieve a 6% agriculture sector growth rate and reduce poverty by 2015.
	Planting for Food and Jobs (PFJ)	2017 - 2022	To modernise agriculture with subsidised inputs and a responsive extension support system.
Economic development	*Coordinated Programme of Economic and Social Development Policies (CPESDP)*	1996 - 2000	To contribute to economic growth, stabilise inflation, ensure food security, supply primary inputs to other sectors, and increase farmer incomes to comparable levels in other sectors of the economy.
	Ghana Poverty Reduction Strategy (GPRS I)	2003 - 2005	To accelerate growth to achieve poverty reduction through increased productivity, creating incentives for private sector participation in agricultural investment and the use of modern production technologies.
	Growth and Poverty Reduction Strategy (GPRS II)	2006 - 2009	To use agriculture as the foundation for economic growth and structural transformation by modernising the sector and strengthening infrastructure.
	Ghana Shared Growth and Development Agenda (GSGDA I)	2010 - 2017	To achieve and sustain macroeconomic stability while placing the economy on a higher path of shared growth and poverty reduction.
	Ghana Shared Growth and Development Agenda (GSGDA II)	2018 - 2057	To address structural development challenges and presents an opportunity to develop a comprehensive development plan responsive to global development commitments (SDGs and African Union's Agenda 2063).

ii. Poor agriculture resource allocation

Besides the low budgetary allocation, more agriculture expenditure goes towards payment of salaries and subsidies as operational costs, while limited funding goes into infrastructure, extension, research and irrigation (World Bank, 2017). Even though the government spends more money on subsidies, the distribution of inputs such as fertilisers and certified seeds has been challenged by frequent delays and inefficiencies in extension services leading to less than the expected boost in crop productivity (Baanni, 2020; Hazel et al., 2019). The delays in distributing subsidised inputs, especially through the PFJ programme, are linked with inefficient public procurement structures, which are bureaucratic and time-consuming, affecting the supply chain of subsidised inputs from producing companies at the national level to farmers at the local level (Baanni, 2020).

Furthermore, the decentralised policy in Ghana, where resources (funding) from the national level are channelled through regional headquarters to district/municipal assemblies for local implementation, has been unsuccessful for many years due to an incomplete governance structure (Padgham et al., 2015). According to the World Bank (2017), the decentralised governance structures deepen institutional constraints, especially the poor capacity for extension services. Inadequate access to resources due to poor funding allocations prevents institutions, especially in Northern Ghana, from developing internal capacity to support farmers to enhance their adaptive capacity for high productivity (Benin, 2019; Yaro et al., 2015).

iii. Inadequate information/knowledge transfer

Public spending on agriculture research and development is about 0.7% lower than the 4% commitment made by the Ghanaian government to improve knowledge and information systems, especially around biophysical risks like poor soils and climate change (Hazel et al., 2019; MOFA, 2017). Poor funding for agriculture research has hindered the collection of quality data forcing institutions to rely on weak data (such as weather and soil information) from the local level public institution (World Bank, 2017). Poor data produced by the public institution could be reduced with adequate funding for training and logistics for data capture and management.

Moreover, Mawunyo and Woedem (2013) found that the top-down agriculture research approach, where institutions rarely engage smallholder farmers about their information/knowledge needs before conducting field research, often leads to poor technology adoption. Participatory research approaches could enable technology adoption and facilitate the efficient transfer of knowledge and skills to enhance farmers' adaptive capacity and productivity (Mawunyo & Woedem, 2013; Naab et al., 2019; Yaro et al., 2015). Also, several studies have noted that the lack of coordination and interaction among institutions, especially between formal and informal sectors, hinders the trust needed for collaboration and partnerships that could enhance information transfer and knowledge exchange (Hazel et al., 2019; Mawunyo & Woedem, 2013).

iv. Biophysical constraints

Several authors have argued that the rapidly changing biophysical risks, including climate change, pest (FAW) invasion, ecosystem degradation and poor soils, are making it difficult for institutions with limited resources (logistics, information and funding) to manage these risks (Boafo et al., 2016; Koffi et al., 2021; Tetteh et al., 2016). Northern Ghana's existing semi-arid and savanna ecological zones, with uni-modal rainfall and limited water resources, are experiencing the worst climatic risks in the country, affecting many livelihoods (World Bank, 2017; Yaro et al., 2015). However, institutions in the region are inadequately equipped with funding to deal with the climatic impact on livelihoods. For instance, several studies have reported that the ineffective adaptation and mitigation options among farmers in Northern Ghana were due to low institutional capacity to enact the right policies or implement effective strategies (Mawunyo & Woedem, 2013; Naab et al., 2019; World Bank, 2017; Yaro et al., 2015). Yaro et al. (2015) found that poor institutional capacity to target vulnerable farmers in Northern Ghana led to maladaptation in some areas instead of reducing biophysical risks.

Furthermore, biophysical risk like FAW has become a constraint to government policies like the PFJ policy, as investments to boost cereal productivity in 2017 were impeded by pest invasion, which affected productivity in Northern Ghana in 2018 (Koffi et al., 2021). Similarly, institutional efforts to implement sustainable strategies to manage and use ecosystem services by rural communities have been challenged by limited alternative livelihood sources and over-dependency on biophysical resources like forests (Boafo et al., 2016; Tesfahunegn et al., 2021; Tetteh et al., 2016). For instance, Boafo et al. (2016) reported that local institutions in Northern Ghana have struggled to use by-laws, customs and rituals as deterrent measures to maintain compliance with environmental management strategies due to socioeconomic and environmental dynamics that deepen food insecurity and poverty in the region. The implications of biophysical constraints (such as unreliable and poor rainfall) are discussed in the research results in Chapter 7 as one of the key factors hindering institutional innovation (See pages 221 and 223).

2.5.3.2 Entry points for institutional innovation and productivity

Even though the constraints affecting institutions in Northern Ghana may be many, studies have shown that several entry points exist internally and externally within institutions to facilitate agriculture innovation and enhance productivity. These entry points include enabling policies, public-private partnerships, institutional coordination/collaboration and local capacity/agency.

Regardless of political philosophy, successive governments in West Africa have committed resources to implement policies that boost crop production (Diao & Hazell, 2019; Hazel et al., 2019; World Bank, 2017). For instance, in Ghana, successive governments since 2000 have found the means to support the objectives of some existing policies like FASDEP II by renaming or modifying those policies (Mawunyo & Woedem, 2013). At least in policy, government commitments to continue existing agriculture policies and programmes could enable a progressive achievement of long-term agriculture goals, which may also drive future policies. Similarly, Diao and Hazell (2019) concluded that policy implementation opportunities to increase institutional capacity and reduce the bottlenecks related to inputs supply value chains could enable the achievement of policy objectives. For instance, the PFJ policies made institutional capacity one of its objectives to enhance extension support for smallholder farmers to use subsidised inputs efficiently (Abdallah et al., 2021; Baanni, 2020).

Furthermore, the partnership between the public and private sectors can increase land and labour productivity for food crops, especially cereals and legumes (Diao & Hazell, 2019). Public-private partnerships have successfully driven agriculture policies in Ghana with funding, resources and technical support. As noted earlier, most of the funding for agricultural policy implementation is donor-funded, which also challenges policy sustainability (Benin, 2019; Hazel et al., 2019; World Bank, 2017). Even though major issues like poor procurement exist within agriculture public-private partnerships, the collaborations between the government and input supply companies have facilitated the PFJ policy across the country (Baanni, 2020; PFAG, 2019). Several studies have argued that due to weaknesses within government structures, the most effective way to reduce inefficiencies within the public sector to boost agriculture may be through private-public partnerships (Benin, 2019; Diao & Hazell, 2019; Hazel et al., 2019). At the community level, institutions like NGOs and CSOs generally access funding and technical support through partnerships with donor agencies or government institutions to achieve mutual developmental objectives, including poverty alleviation, food security and environmental sustainability (Mawunyo & Woedem, 2013; Osei-Amponsah et al., 2018).

Beyond enabling policies and partnership opportunities, studies have shown that coordination efforts among institutions are critical entry points for achieving a productivity boost in Northern Ghana (Diao & Hazell, 2019; Mawunyo & Woedem, 2013). After identifying the lack of cooperation as a shortcoming in previous agriculture policies, subsequent policies to boost productivity have insisted on inter-ministerial and private-sector coordination for implementing policies and programmes (Mawunyo & Woedem, 2013). Evidence shows that institutional coordination facilitates information sharing, policy dialogues and budgetary consolidation to enhance agriculture service delivery (Mawunyo & Woedem, 2013; World Bank, 2017). For instance, the Agriculture Sector Working Group (ASWG) was set up by the Ministry of Food and Agriculture (MoFA) to coordinate inter-ministerial and private-sector policy dialogue to enable effective resource use to achieve policy objectives (World Bank, 2017). Diao et al. (2019) concluded that private and public sector investments in Ghana's agriculture could be streamlined when projects and programme funding activities are coordinated at different levels. Several authors have recognised that the existing and functioning coordinating structures within the cocoa sector could be applied to the food crop sector: for cocoa, relevant institutions have regulations that coordinate their activities to make it easier to achieve policy goals (Diao et al., 2019; Kolavalli, 2019; World Bank, 2017). However, others have argued that the insufficient capacity within the public sector and the different funding mechanisms have hindered effective coordination efforts for policy implementation, especially at the local level (Diao et al., 2019; Mawunyo & Woedem, 2013).

At the local level, institutional coordination is often useful for natural resource management and enhancing the adaptive capacity of communities (Naab et al., 2019; Ofoegbu & New, 2021; Osei-Amponsah et al., 2018; Yaro et al., 2015). However, some studies in Northern Ghana found that institutional coordination in agriculture and climate services did not provide significant benefits to farmers due to weak coordination between national and local institutions for a policy or programme implementation (Ofoegbu & New, 2021; Osei-Amponsah et al., 2018). In most cases, there is decent bottom-up coordination for policy formulation but poor top-down coordination for policy implementation at the local level (Ofoegbu & New, 2021).

Finally, farmers' local capacity and agency are entry points to institutional policy and programme goals. Farmers organize themselves into various social and support groups at the community level to increase labour or mobilise resources to support individual or group livelihood activities (Martey et al., 2014; A. Salifu & Funk, 2012; Yaro et al., 2015). Local institutions often leverage these social groups to advance their policies and programmes. For instance, evidence shows that formal institutions have used groups like the VSLA to advance poverty reduction, environmental sustainability and crop productivity goals among vulnerable groups (Lawson et al., 2019; Yaro et al., 2015). Similarly, Bonye et al. (2012) found that NGOs and government organisations often rely on members of local expertise to conduct field operations such as field demonstrations, training and input distribution. For instance, in collaboration with local institutions, well-organized farming and livelihood groups in Northern Ghana have received funding and technical support directly from national and international donor agencies without government intermediaries (Benin, 2019; Osei-Amponsah et al., 2018). Again, the traditional local authority, including the Chiefs and Queen mothers, serves as an important informal institution that oversees and controls community resources and is known to be the most critical partner in achieving any policy and programme objectives (Boafo et al., 2016; Yaro et al., 2015). The traditional authorities in Northern Ghana act as the gatekeepers of indigenous/local knowledge and practices, enforce by-laws and facilitate community participation in institutional policies or programmes (Boafo et al., 2016; Yaro et al., 2015).

Overall, the studies presented thus far on institutional characteristics to crop productivity demonstrate that public policy is central to most institutional constraints and an entry point to implementing innovative cropping systems like SI. For instance, several studies argued that public policies define resource allocation, information transfer, public-private partnerships and effective collaboration that could enhance crop productivity. Similarly, some authors have also observed that implementing public policies is often challenging as bureaucracies, bottlenecks, and complex structures within the governance system may delay implementation and coordination between the national and local levels to advance innovation and productivity. However, much of what is known in current literature about institutional constraints and entry points, especially on public policy influences in facilitating agriculture innovation, is overgeneralised as the institutions may defer depending on where they operate. Many have argued that, unlike technology that can be replaced at any given point, institutions are not easily replaceable due to their embeddedness within the agriculture system; as such, their role in crop productivity cannot be generalised (Hounkonnou et al., 2012; Totin et al., 2018). Contextualising institutional characteristics in the case study areas is useful for identifying the specific institutional constraints that could affect crop productivity and entry points implementing SI when the agriculture system.

2.7 Methods for assessing the sustainability of agriculture systems

There is no unique set of methodological approaches researchers apply to analyse sustainable agriculture, especially from an SI perspective. Several studies have used diverse methods and approaches depending on the type of agriculture system, the case study, the conceptual framework and the research objectives (Schindler et al., 2015). However, most studies agree on the following as guidelines for analysing most sustainable agriculture systems, which include; *i)* Sustainability domains (pillars or dimensions), *ii)* Sustainability principles (outcomes or goals), *iii)* Sustainability indicators or metrics. Domains represent the overall themes or categories under review; principles are the expected goals or outcomes of the assessment; indicators are the individual variables that make the domains and principles; the metrics are the indicators that are measurable in the agriculture system (De Olde et al., 2016; Pham & Smith, 2014; Schindler et al., 2015). See **Table 6** below for summaries of assessment tools for sustainable agriculture.

2.7.1 Sustainability Domains

Different approaches have been used to assess agriculture sustainability by adopting or modifying existing methods to suit their research objectives. Several assessment tools, including Sustainable Agri-Food Evaluation Methodology (SAEMETH), Monitoring Tool for Farm Sustainability (MOTIFS) and Evaluation of Natural Resource Management Systems (MESMIS – Spanish acronym), use the traditional triple bottom line approach to measure sustainability from three domains: environmental, social, and economic (Fallah-alipour et al., 2018). The limitation of the triple bottom line approach is that it cannot account for other external factors (like institutions) that may have a direct or indirect impact on the agriculture system.

Contrary to the triple-bottom-line approach, other assessment tools have used either a single domain or more than three domains for their assessment. For instance, Sabiha et al. (2016) applied a set of sustainability principles within a single domain (environment) to assess high-yielding rice production in three agriculture systems in Bangladesh. The single-domain assessment can help provide a detailed assessment of a specific domain, but the results could be biased and limit the true reflection of sustainability in the agriculture system. Other assessment methods, including the Scaling up of good agricultural practices (ScalA) and the Sustainability Assessment of Food and Agriculture Systems (SAFA), try to address the limitation within the triple bottom line approach by adopting a more robust approach that embraces different domains (especially governance and productivity) besides these traditional triple-bottom line domains (FAO, 2014a; Musumba et al., 2017). The limitations of these approaches are that they are less flexible and must be applied strictly for the analysis regardless of the case study or the type of agriculture system under review.

The limitations in domain selection are addressed with the SI concept, which is flexible and often dependent on the study's objectives and case study site. Some SI case studies in SSA (Musumba et al., 2017; Snapp et al., 2018b) selected 5 sustainability domains, including productivity, environmental, social, economic and human conditions to analyse the sustainability of cereal production in Africa. However, several SI studies conducted in SSA, especially in West Africa (Dakyaga et al., 2020b; Hoeschle-Zeledon, 2021; Kotu et al., 2017) fail to include or adequately address institutions as a critical component of the agriculture system. Pretty et al. (2011) argue that institutional characteristics of an agricultural system define how environmental and socioeconomic components are governed, accessed and used to enhance crop productivity or promote innovative cropping systems; as such, they need to be included in understanding sustainable cropping systems.

2.7.2 Sustainability Principles

The set of sustainability principles (outcomes, goals or criteria) for guiding the assessment of sustainable agriculture is also differently defined by different studies (Schindler et al., 2015). In some studies, sustainability domains and principles are used interchangeably, while others consider them separately to clarify the outcomes expected from the agriculture system (Schindler et al., 2015; Struik & Kuyper, 2017). For instance, Musumba et al. (2017) frequently interchanged sustainability domains with principles in their assessment of maize sustainability in Malawi, suggesting that the domains are also the expected outcomes. On the contrary, Meul et al. (2008) separated their three domains (environmental, social and economic) from their ten expected outcomes (internal social sustainability, external social sustainability, disposable income, input use, natural resource quality, entrepreneurship, productivity and efficiency, profitability and economic risks management) in their work on sustainability in the Flemish dairy farms. From these studies, it is observed that sustainability analysis with many indicators often uses principles to produce clarity in the analysis and clearly define the expected outcomes of the study.

Furthermore, Fallah-alipour et al. (2018) emphasised that since the agriculture system is a social construct, its sustainability principles should address local needs, including farmers' well-being, farm productivity and agriculture resource conservation. The MESMIS framework proposes six principles/outcomes: productivity, equity, self-reliance, stability, reliability, and adaptability. Other frameworks, such as the SAFA assessment tool proposed by FAO, suggest as many as twenty-one outcomes for assessing sustainable agriculture due to the wide range of indicators the methodology covers (FAO, 2014a; Speelman et al., 2007). Most studies reviewed do not adequately address climate change as part of agriculture sustainability outcomes except for the ScaleA assessment tool that integrates climate change responsiveness within all sustainability domains (Crewett, Bringe, et al., 2006).

The SI concept does not have a unique set of principles; however, productivity and efficiency are critical expected outcomes for sustainability and intensification to operate within the same agriculture system (Struik & Kuyper, 2017). Considering the environmental challenges like climate change that affects crop productivity and social factors like gender inequalities (especially for land) in SSA and West Africa, environmental resilience and social equity need to be considered as expected outcomes or principles from an SI perspective.

2.7.3 Sustainability Indicators

Sustainability principles/outcomes are used as the criteria to delineate indicators to be selected as part of the assessment process. The selection process used by some studies is either participatory (stakeholder-expert determination) or expert/researcher determination. According to Lopez-Ridaura (2005), selecting indicators through a rigorous review by researchers/experts allows the indicators to be adequately streamlined to cover both the domain and sustainability principles to produce robust, reliable, measurable indicators. Meul et al. (2008) used the participatory approach differently to engage stakeholders on the indicators they could not establish in literature, especially on social themes. Other participatory approaches like SAFA, MOTIFS, SAEMETH, and ScaleA engaged stakeholders to determine the indicators for all domains (Crewett et al., 2006; FAO, 2014a; Musumba et al., 2017; Peano et al., 2015). Primarily, researchers conduct the indicator selection process before collecting data from the field. However, Gaviglio et al. (2016) first identified indicators through data collection before applying 15 sustainability principles for the three domains within the agroecological system. Highlighting the need to select an appropriate indicator selection process, Gómez-Limón & Sanchez-Fernandez (2010) noted that indicators identified through expert elicitation or a participatory process should be reliable, policy-relevant and easy to measure.

Two categories of indicators exist when analysing sustainable agriculture systems: input and driver indicators. Input indicators are capitals (natural, social, manufactured, human and economic) that are found within the agriculture system itself and are used to enhance crop productivity (Smith et al., 2017). The role of the 5 capitals in SI literature has been overgeneralised and not considered in most SI conceptual framing. However, most studies discuss the pillars and principles of SI within the 5 capitals framing but are not explicitly classified as such. The present study argues that since input indicators cover a wide range of factors, recognising the 5 capitals in conceptual framing helps put these indicators into perspective. Also, the driver indicator is the internal and external factors (such as demography, population, capacity, gender, and education) that influence the input indicators within the system (Pham & Smith, 2014). For instance, external investment into the agriculture system could enhance natural and social capital to achieve SI goals (Smith et al., 2017). Identifying and analysing these drivers can help establish a critical relationship between them and input indicators, enhancing the results of any agriculture sustainability studies (Fallah-alipour et al., 2018; Pham & Smith, 2014).

Some previous SI studies have used stakeholder engagements to select the indicators to consider for analysing any agriculture system (Kotu et al., 2017; Musumba et al., 2017; Smith et al., 2017). This engagement often considers higher-level expertise to determine what needs to be included in the indicator selection. However, this process can be expensive and lacks local stakeholder inputs. This study resolved this limitation with an initial desktop review of expert-reviewed indicators from previous SI studies and a follow-up review of these indicators with local stakeholders within the case study areas.

After indicator selection, the next step is to analyse sustainability through a composite or an indicator-based approach which often centres on the objectives of a study (Schindler et al., 2015). According to Musumba et al. (2017), analysing sustainability by an indicator-based approach helps simplify the details of a complex system and supports stakeholders (especially policymakers) to be strategic with policy and implementation actions. On the contrary, the composite-based analysis used by Gómez-Limón and Sanchez-Fernandez (2010), Pham and Smith (2014) and Gaviglio et al. (2016) enabled researchers to make conclusions on the sustainability of the whole agriculture system or a specific domain. The difference between these approaches is that indicator-based approaches apply metrics to individual indicators, while composite-based approaches combine metrics from individual indicators to product an index based on SI domain (Social and economic) or principle (productivity and efficiency).

***Table 6**: Summaries of assessment methods used in different sustainable agriculture studies (Compiled from literature)*

Study	Domain and sustainability criteria	Case study	Selection of indicators	Measurement	Relevance for the present study
Fallah-Allipur et al., 2018	3 Domains *(Environmental, social, and economic)* under 3 principles, 9 indicators	Crop systems in Kerman, Iran	Stakeholder and Expert	Quantitative: Composite based using normalisation (0,1), Fuzzy pairwise comparison, Analytical Hierarchy Process	Indicators and drivers for agriculture sustainability
Musumba et al., 2017	5 Domains *(productivity, environmental, economic, social, human)* with 39 overall components, 15 principles	Cereal production in Malawi and Ghana	Stakeholders and Expert	Mixed: Indicator-based using normalisation process (0,1)	The introduction of different domain dimensions and the strength in indicator connections
Gaviglio et al., 2017	3 Domains *(Environmental, social, and economic)*, 15 principles, 50 components, 250 indicators	Crop farms in Milan, Italy	Expert/researcher	Mixed: Composite based using descriptive statistics SD and percentages for scoring/weighting	The use of descriptive statistics to find relationships among indicators
Meul et al., 2008 (Monitoring tool for farm sustainability-MOTIFS)	3 Domains *(Environmental, social, and economic)*, 10 components,	Flemish dairy farms in Belgium	Stakeholders and Expert	Mixed: Composite based on equal application of weights at all principles and domains except when necessary	The use of equal weighting for domains unless decided by stakeholders
Peano et al., 2015 (Sustainable Agri-Food Evaluation Methodology-SAEMETH)	3 domains *(Environmental, social, and economic)* under 11 components, 52 indicators	Small-scale agrifood systems in Italy	Stakeholder engagement	Mixed: Composite based on normalisation (1,10) and weighting done equally to all indicators	Stakeholder engagements and equal weighting
Crewett et al., 2006 (Scaling up of good agricultural practices-ScalA)	3 Domains *(Environmental, social, and economic)*, 61 indicators with the inclusion of climate change factors	Multiple developing countries in Africa and Asia	Stakeholder engagement	Mixed: Composite-based normalisation (0,100)	Considers climate change as an essential sustainability principle
Lopez-Riduara et al., 2005 (Evaluation of Natural Resource Management Systems -MESMIS)	3 Domains *(Environmental, social, and economic)* classified under 5 principles	Natural resource management in small farms in Mali	Stakeholder engagement	Mixed: Composite-based using normalisation and weighting metrics	Stakeholder engagements and equal weighting
Kaufman et al., 2010 (World Governance Indicator-WGI)	1 Domain *(Institutional)* with six principles	Global governance indicators	Expert review	Mixed but more qualitative: Indicator-based using normalisation and equal weighting metrics	Global standards for governance indicators
Pham and Smith, 2013	3 Domains *(Environmental, social, and economic)* and 3 drivers of sustainability	Small-scale farming in Vietnam	Expert-stakeholder review	Mixed: Indicator-based using descriptive statics (Regression models) to establish a relationship between drivers and domains indicators	Indicators and drivers. The use of descriptive stats to establish relationships
Sabiha et al., 2016 (Composite environmental impact index-CEII)	1 Domain *(environmental)* 17 indicators grouped under 3 components	Rice production in Bangladesh	Expert review after data collection	Mixed: Composite based but within a single Domain. Normalization (0,1) and weighting done.	Composite aggregation method within environmental domain
Gomez-Limon and Sanchez-Fernandez, 2010	3 Domains *(Environmental, social and economic)* with 16 principles	Irrigated and rainfed systems in Spain	Expert review	Mixed: composite based with normalisation and multi-criterion function weighting (sum + product aggregation)	Multi-criterion approach based on compensation and partial compensation
FAO, 2014 (SAFA)	4 Domains (Environmental, social and economic and institutional) with 21 principles	Global food systems	Stakeholder and expert review	Qualitative	Includes governance in the approach

Due to the interdisciplinary nature of agriculture sustainability assessments, many studies reviewed have employed quantitative metrics, which may then be normalized, weighted, or aggregated to make a judgement on the overall sustainability of agroecological systems (Pham & Smith, 2014; Sabiha et al., 2016; Schindler et al., 2015). However, little attention has been given to qualitative metrics in SI analysis and sustainable agriculture, even though stakeholder engagement processes may be used in indicator selection. Even though mixing metrics is a strength for assessing the sustainability of agriculture systems, researchers struggle with issues around weighting (equal or unequal weighting) and aggregation of indicators (as index) and the domains to consider (Gómez-Limón & Sanchez-Fernandez, 2010). The present study argues that quantitative and qualitative metrics should be considered/analysed separately, and the results should be used as complementary information to provide context to each other.

2.7.6 Methods for stakeholder engagement

As noted earlier, the integration of qualitative analysis in sustainable agriculture studies has been limited, especially for SI studies. Several studies have established that institutions (formal or informal) are one of the irreplaceable components of the agriculture system that drive innovation and technology for sustainable farming (Pretty et al., 2011; Totin et al., 2018). The present study uses stakeholder engagements with local institutions to collect qualitative data that compliments quantitative data from surveys.

Agriculture systems are complex and have many layers of competing and interrelated actors. Many studies have argued that the complex nature of agriculture systems, including layers of biophysical and socioeconomic factors, require multidimensional assessment using methodologies that embrace diverse quantitative and qualitative approaches (Dumont et al., 2019; Mulema et al., 2021; Sparrow & Traoré, 2018; Winowiecki et al., 2021). Multi-stakeholder engagement approaches may be useful for understanding these complexities within the agriculture system (Adekunle & Fatunbi, 2012). These approaches, through stakeholder perspectives, could provide opportunities to enrich the existing scientific evidence through the co-production of knowledge, allowing a deeper understanding of the contexts and complexities within the agriculture system (Adekunle & Fatunbi, 2012; Furman et al., 2018; Sparrow & Traoré, 2018). According to Sparrow and Traoré (2018), the failure of technology and innovation transfer within the agriculture systems in sub-Saharan Africa is largely due to poor stakeholder engagements, as scientific approaches often neglect local knowledge during research and implementation of projects.

Various multi-stakeholder engagement approaches for agriculture development in Africa have been characterised by their purpose, target audience and methods, as shown in **Table 7** below. The purpose of selecting a multi-stakeholder approach for a study may depend on its ability to facilitate inclusivity, collaboration, innovation, policymaking and transformation of the agriculture system (Furman et al., 2018). The target audience for multi-stakeholder approaches is often stakeholders at the national level who influence policy (Mulema et al., 2021; Schut, Cadilhon, et al., 2016) or those at the local level who participate in implementation activities (Chinseu et al., 2022; Dumont et al., 2019). However, some approaches target national and local stakeholders for a more holistic perspective that could influence policy and practice (Winowiecki et al., 2021).

Table 7: *Summary of approaches used for muti-stakeholder information gathering for agriculture productivity.*

Tool	Type and purpose	Where (target)	Method	Pros	Cons
Integrated Agricultural Research for Development (IAR4D) *(Adekunle & Fatunbi, 2012; Schut, Cadilhon, et al., 2016; Sparrow & Traoré, 2018)*	Using "innovation platforms" as facilitating network between farmers and agriculture value chain stakeholders to improve the well-being of smallholder farmers.	Local stakeholders in Senegal, Burkina Faso, Cameroon, and Chad	Innovative platforms for the livestock market and its value chain. Series of meetings and training on specific themes such as value milk and meat value chain	• Approached builds upon existing development research. • Frequent monitoring and valuation activities. • Active socioeconomic data collection among participants that enables tracking of progress	• Focus on market systems than actual production. • The model is less beneficial to subsistence agriculture based on markets and value chain development. • Engages middle-class stakeholders than farmers
Engagement, synthesis, and support in gender (GSI) *(Mulema et al., 2021)*	Gender-inclusive platforms to increase climate change resilience among men and women in Africa through policy making.	National stakeholders in Burundi, Djibouti, Eritrea, Ethiopia, Kenya, Nigeria, South Sudan, Sudan, Tanzania, Rwanda, and Uganda; Papua New Guinea	Webinars, meetings, training/ workshops, and communication through social media channels	• Ability to increase the capacity of stakeholders to be gender sensitive in policymaking • Targets stakeholders at the highest level with the capacity to cause change	• More emphasis on national-level stakeholders than local-level stakeholders • More emphasis on influencing policymaking than influencing practice
Policy action for climate change adaptation (PACCA) *(Mulema et al., 2021)*	Gender analysis of agri-food and climate policies and budgets to inform the Policy Action for Climate Change Adaption, climate scenario analysis to inform policy.	National stakeholders in Uganda and Tanzania	Desk reviews, workshops, validation meetings, multi-stakeholder platforms at district and national levels, info-notes, interviews	• Broader stakeholder engagement activities • Diverse data collection procedures • Engagements are based on evidence than perceptions	• The process may be time consuming • More emphasis on influencing policymaking than influencing practice
Structured stakeholder engagement for diversity and inclusive agroforestry options *(Dumont et al., 2019)*	Muti-stakeholder engagement platforms for building local knowledge on production and conservation at different scales that enable suitable agroforestry options	Local stakeholders in the Democratic Republic of Congo (DRC)	Scoping field study, Stakeholder workshops and training	• Muti-stakeholder engagement procedure with diverse groups • Detailed local knowledge generation about conservation and production within the study area	• Limited in scope (only focus on agroforestry as an option for productivity) • Time and resource-consuming to replicate
Agricultural innovation system [AIS] approaches *(Chinseu et al., 2022)*	Identifying the roles, capacity, and collaboration of key stakeholders in the development of conservation agriculture	Local and national stakeholders in Malawi	A comprehensive process with key institutions to select relevant stakeholders, key informant interviews and document analysis	• Capable of selecting the right stakeholders to engage • The use of scientific evidence to triangulate stakeholder interviews • Promotes local-level innovation	• Lack of interaction and collaboration among diverse stakeholders as engagements are done within institutions • The approach may be time-consuming for research with limited time

Transformative scenario planning (TSP) *(Sidiki Alare et al., 2017)*	Muti-stakeholder engagements to transform the future complex systems such as climate change and food security	Local stakeholders in Ghana	Stakeholder selection, Series of workshops and meetings to develop future scenarios	• Engages diverse stakeholders • Facilitates collaboration and problem-solving among stakeholders • Capable of highlighting key thematic areas for research • Good for policy development	• Scenarios are based on stakeholders' perspectives than scientific evidence • The process can be resource demanding and time-consuming
A stakeholder approach to risk-informed and evidence-based decision-making (SHARED) *(Winowiecki et al., 2021)*	Developing sustainable pathways for sustainable intensification through scientific evidence and stakeholder engagements	National and local stakeholder groups in Ethiopia, Tanzania, and Zambia	Stakeholder mapping, participatory tradeoff analysis, data collection, stakeholder workshops and the co-development of the decision dashboard	• Capable of selecting the right stakeholders to engage • The use of scientific evidence to triangulate stakeholder interviews • Facilitate co-designing of tools for decision-making	• The process may be hectic for some stakeholders to comprehend • The use of the decision dashboard may be technical for local stakeholders • The process can be resource demanding and time-consuming
Regional/national synthesis, engagement, and support in West Africa *(Mulema et al., 2021)*	Developing a gender, climate, and agriculture profile of Ghana	National stakeholders in Ghana	Science-policy dialogue platforms (national and district)	• Ability to increase the capacity of stakeholders to be gender sensitive in policymaking • Targets stakeholders at the highest level with the capacity to cause change	• More emphasis on national-level stakeholders than local-level stakeholders • More emphasis on influencing policymaking than influencing practice
Rapid Appraisal of Agricultural Innovation Systems (RAAIS) *(Schut, Klerkx, et al., 2015; Schut, Rodenburg, et al., 2015; Schut, van Asten, et al., 2016)*	For diagnosing institutional constraints and providing entry points for agriculture innovation such as Sustainable intensification within complex agriculture systems	Local and national stakeholders in Ghana, Tanzania, Malawi, and DRC	Workshops, interviews, and surveys	• A multidimensional approach to assessing constraints and entry points • Solution-oriented approach for data collection and co-production of innovation • Less complex to replicate	• No feedback loop to stakeholders for reflection

From **Table 7** above, the multi-stakeholder engagement methods regularly used for institutional appraisal or assessments include stakeholder consultative platforms, workshops, key informant interviews and surveys. Some approaches may combine different methods for research purposes while also serving as a platform for learning, collaboration and co-creation of solutions (Furman et al., 2018; Schut, Klerkx, et al., 2015). Besides the advantages, such as being a complementary tool for broader research and the richness of diversity in perspectives, some of these approaches may be complex to replicate and demand intensive resources and time to complete. Also, some of these methods are quick, and others are in-depth; some are appropriate for technical staff at national and local levels; others are appropriate for local people to understand.

However, this study employed the Rapid Appraisal of Agricultural Innovation Systems (RAAIS) approach to assess the institutional constraints and entry points for SI in Northern Ghana. The RAAIS is a multi-stakeholder diagnostic tool designed to understand the complex constraints of the agriculture system and provide specific and generic entry points to address those challenges

(Schut, Klerkx, Rodenburg, Kayeke, Hinnou, et al., 2015b; Schut, Rodenburg, Klerkx, Kayeke, van Ast, et al., 2015; Schut, van Asten, et al., 2016). The approach was developed to build upon the widely used Agricultural Innovation System (AIS) approach, which has limitations in its availability, scope and methods for assessing multidimensional agriculture systems (Schut, Klerkx, Rodenburg, Kayeke, Hinnou, et al., 2015b). The RAAIS framework has the potential to provide holistic and multi-level perspectives with diverse stakeholder groups using both quantitative and qualitative processes to analyse and provide innovative solutions for agriculture development (Schut, Klerkx, Rodenburg, Kayeke, Hinnou, et al., 2015; Schut, Rodenburg, Klerkx, Kayeke, van Ast, et al., 2015).

The RAAIS approach was adopted for this study due to its simplicity in replicating within the shortest possible time with limited resources, which most multi-stakeholder approaches reviewed lacked. Again, the RAAIS's ability to use qualitative data (from the workshop and key informant interviews) with quantitative data (from field surveys) made the approach convenient for the present study, which has a mixed-method approach for data collection. Furthermore, the RAAIS approach has been used for similar SI studies in identifying the constraints and entry points for agriculture innovation in dry areas in Central Africa (Schut, van Asten, et al., 2016). However, the challenge with using the RAAIS approach is that it does not include a feedback loop approach where outcomes of the diagnostic analysis are presented to stakeholders for reflection and updates (Schut, Klerkx, Rodenburg, Kayeke, Hinnou, et al., 2015b).Overall, the presented studies in this section showed no unique methods for analysing sustainable agriculture systems. However, several authors agree that some basic elements, including domains, principles/outcomes, indicators and metrics, must be well-defined when analysing sustainable agriculture systems. Others have argued that not all elements may be needed and that some elements could be used interchangeably, especially domains and principles components. The major debate among researchers in analysing sustainable agriculture is whether the metrics used should be indicator-based or composite-based. Although both strategies may have strengths and weaknesses, selecting the appropriate one depends on the study's context and objectives (Musumba et al., 2017; Schindler et al., 2015). The present study argues that indicator-based and composite-based metrics can be used together to analyse agriculture systems when appropriate.

Further, most of the methods used in the reviewed studies fail to adequately account for indicators such as equity and institutions, which are qualitative metrics in their analysis of sustainable agriculture systems. In West Africa and Northern Ghana, where cultural norms exacerbate inequalities and institutions are critical components of the agriculture system, equity as a principle/comes and institutions as a domain is necessary. The present study included these elements in its SI conceptual farming to enable a robust analysis of the agriculture system. Also, the possible reason for fewer qualitative metrics in most sustainable agriculture analyses, especially the framework for most SI studies, is that they are often used as monitoring and evaluation tools for interventions/technologies, which may require more quantifiable outcomes. The limitation of using SI as a Monitoring and Evaluation tool for interventions or implemented technologies is that they may be biased or limit local capacity (knowledge or practices) that are useful for sustainable agriculture. The present study argues that the SI framework should be used to analyse existing agriculture systems to understand the system's barriers and enablers before appropriately applying intervention or technology.

2.8 Summary

Biophysical and socioeconomic constraints are presenting new challenges for crop production systems where food demand may outpace production at the global, regional and local levels if these constraints are not addressed timely. At the regional level, several studies point to the complexities of biophysical and socioeconomic events that have guided the transition of the crop production system from its earliest subsistence nature to a later livelihood activity. As conventional farming systems struggle amidst these complexities, new farming systems have emerged to create a win-win for productivity and environmental sustainability. However, most of these sustainable systems, including their analysis methods, are often not comprehensive as they focus on resolving biophysical constraints and less on socioeconomic characteristics that may have long-term implications for the agriculture system. The SI concept has been proposed as a robust pathway to addressing the gaps within sustainable farming systems as it takes a holistic approach to agriculture productivity and sustainability.

However, the following gaps remain in current SI literature; *i)* SI framework has become more intervention/technology-based approach and less on understanding the local characteristics/knowledge of existing cropping systems, *ii)* most SI studies fail to adequately account for equity issues and institutional role in agriculture system governance, and *iii)* there is limited knowledge of assessing crop production system in localised contexts in semi-arid Northern Ghana from SI perspective. This PhD study addresses these gaps by; *i)* identifying and comparing the biophysical, socioeconomic and institutional characteristics of the current cropping systems that contribute to crop productivity differences in RVB and BVB of semi-arid Northern Ghana, *ii)* discussing how these known characteristics will have implications for SI principle/outcomes/goals (including productivity, resilience, efficiency and equity) in the case study areas, and *iii)* developing an SI conceptual framework that considers institutional domain and equity outcome for a comprehensive assessment of semi-arid cropping systems in West Africa.

CHAPTER 3
METHODOLOGICAL APPROACH

3.1 Introduction

This PhD aims to determine the factors contributing to productivity differences between RVB and BVB and how these factors could influence the implementation of SI within smallholder agriculture systems in semi-arid Northern Ghana. The study's objectives are to assess and compare the biophysical, socioeconomic and institutional characteristics of the smallholder agriculture systems in the two basins, and how these could hinder or enable SI in Northern Ghana. This chapter describes the methodological approach adopted to achieve these research aims and objectives. This section describes the conceptual framework and research design, followed by data collection methods, analysis techniques, study limitations, and ethical considerations.

3.2 Conceptual Framework

The conceptual framework for the present study draws on sustainable agriculture and SI frameworks used in previous studies for analysing crop production systems in SSA (van Loon et al., 2019; Musumba et al., 2017; Smith et al., 2017a; Snapp et al., 201). The present study aims to determine the factors contributing to productivity differences between RVB and BVB and how these factors could influence the implementation of SI within smallholder agriculture systems in semi-arid Northern Ghana. Theoretically, this framework consists of the SI domains/pillars (major themes), principles (expected outcomes from indicator analysis) and indicators/variables (inputs and modifiers).

3.2.1 SI domains

Following the domains used by FAO (2014) in the SAFA framework, the present study classifies indicators under four agriculture sustainability domains/pillars, namely environmental, social, economic and governance/institutional. The four domains depart from several studies using the triple bottom line approach, which considers environmental, social and economic themes for their conceptual framing in assessing sustainable agriculture systems (Crewett & Sieber, 2006; Gaviglio et al., 2016; Peano et al., 2015). The triple bottom line approach is useful for the present study's conceptual framework as biophysical and socioeconomic complexities have defined the West

African agriculture system for years, dictating how cropping systems are currently done in the region.

However, the triple bottom line approach fails to address the governance/institutional structures within the agriculture system that could enable sustainable farming and increased crop productivity. Schindler et al. (2015) emphasised that internal and external governance or institutional structures are critical components of an agricultural system and its development and should therefore be included in any agriculture system analysis. Totin et al. (2018) further argue that the role of institutions in agriculture sustainability is inevitable as they are often the pivot for innovation/technology transfer that enhances crop productivity. The inclusion of institutions as a domain for the present study reflects the local context in Northern Ghana, where institutions are critical to the overall functioning of the agriculture system, especially for how agriculture inputs and services inputs are distributed, accessed and used for crop productivity (Dakyaga et al., 2020b; Donkor et al., 2016; Yomo et al., 2020).

3.2.2 SI principles

Based on the objectives and context, researchers can judge what principles (outcomes/goals) should be included as outcome indicators in determining sustainable agriculture systems (Schindler et al., 2015). The sustainability principles considered for sustainable agriculture in the present study include productivity, efficiency, resilience and equity.

The productivity of an agriculture system through yield increase is fundamental to any sustainable agriculture framework, especially for SI. Even though the approach may be debatable, several studies have widely agreed that food production must be increased, notably in SSA, to meet the growing food demand from population growth (Cassman & Grassini, 2020; Godfray et al., 2010; Pretty et al., 2011). Others have also insisted that since crop production is tied to agricultural livelihoods, productivity should include economic outcomes like increased incomes (Musumba et al., 2017). However, SI demands that productivity be intensified per unit area rather than expanding cultivated areas, which has historically been the case for most crop production systems in SSA, especially in West Africa (Campbell et al., 2014; Musumba et al., 2017). Besides increased yields and incomes, productivity outcomes may also include yield expectations, biophysical risks that may hinder increased yields and the utilisation of yields (consumption or sales). Productivity outcome is relevant to the present case study in semi-arid Northern Ghana due to its low food crop production levels in some areas than others, even though household livelihoods and food security needs are tied to agriculture.

Furthermore, the SI concept emphasises that intensification to increase yields per unit area should not come at the expense of environmental degradation such as from pollution and waste from input used (Cassman & Grassini, 2020; Pham & Smith, 2014; Smith et al., 2017). Many authors assert that intensive input/technology use is unavoidable if farmers aim to increase productivity without cropland expansion (Musumba et al., 2017; Pretty et al., 2011; Smith et al., 2017). However, input efficiency is one of the outcomes of SI that differentiates the concept from other sustainable agriculture frameworks (Pretty et al., 2011; Smith et al., 2017). Besides direct input efficiency, agriculture services that support farmers with the resources, including advisory to apply inputs efficiently, are considered part of the SI efficiency outcome (Pretty et al., 2011). The present study considers efficiency as an SI outcome for the present study due to the government of Ghana's push to increase input use (fertiliser and improved seeds) and technical advisory through extension services to boost crop production, especially for low-productivity areas of Northern Ghana.

External risks like climate change adversely affect the fragile semi-arid agroecological systems of West Africa, exacerbating existing vulnerabilities (IPCC, 2022; Sultan & Gaetani, 2016). Several studies have shown that climate will affect food security and livelihood outcomes, especially for the most vulnerable communities (Campbell et al., 2014). Promoting environmental and socioeconomic resilience through off-farm and on-farm strategies must be considered part of SI outcomes to ensure sustained productivity and efficiency amidst climatic risks (Garnett & Godfray, 2012; Robinson et al., 2015a). Pretty et al. (2011) assert that SI systems should be able to build ecological resilience strong enough to reduce stress and shocks from environmental impacts. Several pieces of evidence show that climate change severely affects food crop production and the livelihood of many households in semi-arid Northern Ghana (Pinto et al., 2012; Yaro et al., 2015). This evidence provides the basis for including resilience as an expected SI outcome for the present study.

A limitation of most SI conceptual framings, especially in the SSA context, is that they fail to highlight social issues like equity perpetuated by cultural norms within most cropping communities in the region (Fischer et al., 2020; Smith et al., 2017). Other studies considering equity only focused on gender inequalities, neglecting the intersectionality between social groups. Intensifying agriculture production systems have been contested as inequitable, especially with the distribution of agriculture resources (inputs and services) among different social groups (Adenle et al., 2019; Garnett et al., 2012). In semi-arid Northern Ghana, where cultural norms are critical for assessing agricultural resources (inputs and services) (Lawson et al., 2020; A. L. Wood et al., 2021), the present study argues that besides achieving a productive, efficient and resilient cropping system, SI must ensure equitable outcomes that benefits all social groups.

3.2.3 SI Indicators

SI indicators may be considered input indicators or modifier/driver indicators. Input indicators (human, natural, social, financial, and manufacturing capital) are the variables needed to achieve SI outcomes within each domain. Drivers/modifiers of sustainable agriculture are the external or internal variables that could influence how inputs indicators are distributed, accessed and used within the cropping system. Input indicators and modifiers influence each other to determine the SI outcomes achieved within a cropping system (Pham & Smith, 2014). For instance, household size and cultural norms, considered modifier indicators, have long been documented to affect how inputs are accessed locally (Fallah-Alipour et al., 2018b; Pham & Smith, 2013, 2014). Researchers must recognise the relationships and interactions between inputs and modifiers and their influence on SI outcomes as part of the conceptual framing. These relationships also help reduce multiple indicator counts during the assessment and help clarify which indicators are most relevant or critical based on the expected SI outcomes (Garnett & Godfray, 2012).

Figure 3 below describes how SI indicators and outcomes are classified under biophysical, socioeconomic and institutional domains. However, the various indicators (inputs and modifiers) interact to determine how SI outcomes of productivity, resilience, efficiency and equity are achieved.

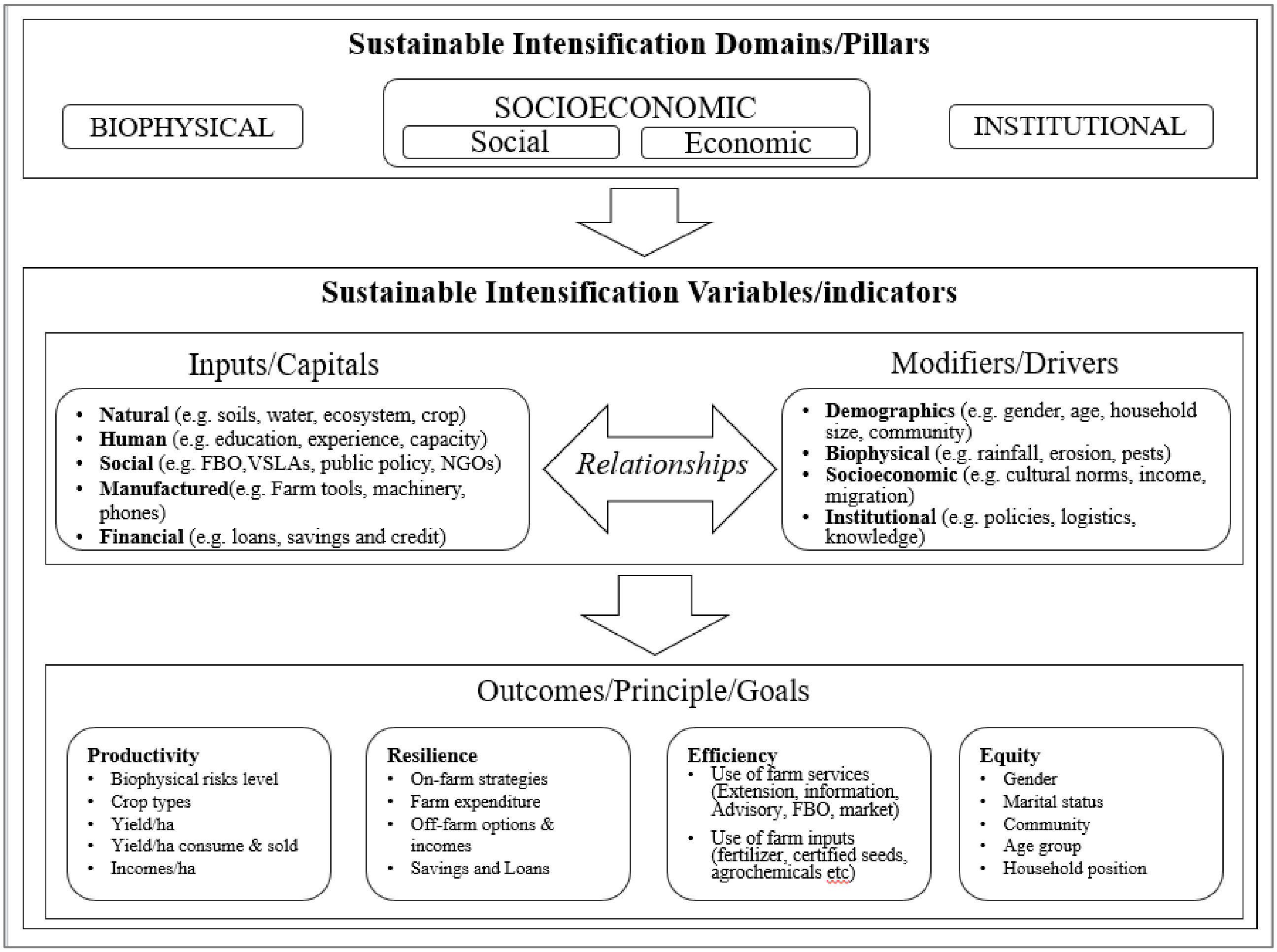

Figure 3: Conceptual framework developed by the researcher based on several studies. (*The SI pillars refer to the four broad dimensions upon which SI depends, and which are assessed as the thesis objectives with social and economic dimensions assessed as one. The SI indicators are the specific factors within each domain that are assessed in the study as inputs or drivers that produces the SI outcomes/principles).*

3.3 Research Design

The research design adopted for this study was multifactorial and integrated due to the cross-cutting nature of the study's conceptual framework. The conceptual framework designed for the study shows the integrated approach, including the pillars, outcomes/goals, and indicators (inputs and modifiers) within the agriculture system. The research design in this study was adopted from the research onion model, which describes research design in systematic stages, including the research's philosophy, approach, strategy, time horizon and techniques/procedures (Melnikovas, 2018). The onion model for research design was useful because it provides the guidelines for selecting a suitable methodological process for the study. **Figure 4** below shows the onion research design adopted for the study.

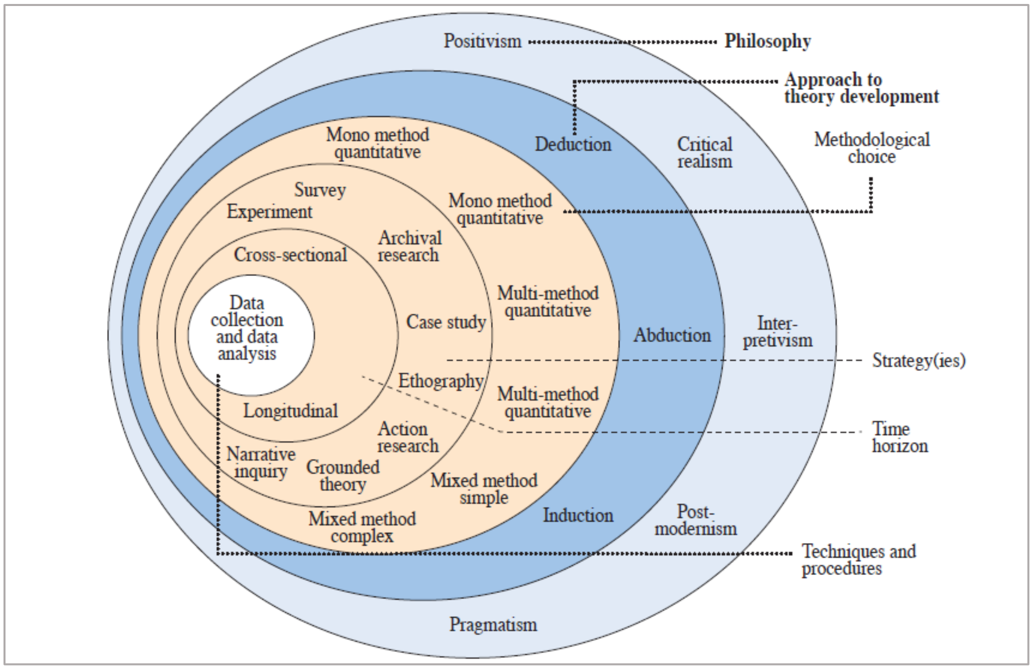

Figure 4*: Research Onion model showing the research design from the outer to inner layers, including philosophy, approach, strategy, time horizon and techniques/procedures of the present study* (Melnikovas, 2018)

The philosophical paradigm chosen for the study was the pragmatism research philosophy rather than the positivism and interpretivism philosophical paradigms. According to Collins and Hussey (2014), pragmatism research philosophy *"contends that the research question should determine the research philosophy and that methods from more than one paradigm can be used in the same study"*. This research philosophy is conducted when the research phenomenon cannot be fully explored with qualitative or quantitative but combines the two approaches (Collins & Hussey 2014). Based on the conceptual framework, the present study combines the agriculture system's biophysical, socioeconomic and institutional domains to understand how SI outcomes can be achieved in RVB and BVB. The present study's multi-dimensional approach considers quantitative and qualitative indicators through secondary and primary data sources to address the research aim and objectives. The pragmatic philosophical approach enabled the study to integrate different factors and methodologies within the agriculture system at the farm and household levels (Scheierling et al., 2016).

Furthermore, the study used the abductive research approach instead of the inductive and deductive approaches due to the aim of the research to find explanations for the differences in productivity levels in RVB and BVB by using the SI framework. The abductive approach is a pragmatic research type that reduces the weaknesses of the inductive and deductive approaches and presents an alternative that combines the strengths of both approaches. While the inductive approach conforms to existing theories and the deductive approach explores new theories, the abductive approach provides explanations for known facts or evidence about the study and can generate new theories or reemphasise existing theories (Saunders et al., 2019). Even though the present study is closer to a deductive than inductive study due to the SI framework used, it also justifies using the abductive approach to explaining reported productivity differences between basins, which strongly informed the study's aim.

Also, the study relied on a case study approach to explore the data collection methods and how to apply them (Melnikovas, 2018). The case study research strategy for the study focuses on understanding crop production factors, including on-farm and off-farm perceptions and strategies that lead to productivity differences between two geographical areas with similarities in ecological and physical characteristics even though they are in different administrative regions of Ghana. In-depth primary and secondary data collection and analysis were conducted to understand the factors dictating crop productivity within the RVB and BVB of Northern Ghana. The results from each case study were useful in the comparative study to understand the crop productivity differences and how SI can help support a productive agriculture system.

The time horizon for the present study was more cross-sectional than longitudinal due to the focus on the present or short-term factors (risk and strategies) and how they can hinder or enable agriculture productivity in the future. The period for the PhD data collection was only a year, making a longitudinal approach impossible for the present study. According to Melnikovas (2018), the aim and objectives determine the timeframe needed to collect the data for a specific study. However, due to time constraints, long-term primary data could not be collected for indicators identified within the two case study areas. The study mostly depended on the primary short-term seasonal perception and strategies of respondents' biophysical, socioeconomic, and institutional experiences within the agriculture systems. Nevertheless, secondary data sources from the DOA provided some longitudinal data for rainfall and crop yields which were helpful for comparison with the short-term primary data collected. Techniques and procedures for data collection and analysis are discussed in detail in the following sections.

3.4 Data collection and analysis technique

This section describes the mode of collection and analysis for quantitative and qualitative data in the case study areas. Two data collection and analysis procedures were followed to examine the different objectives. Objectives 1 and 2 were carried out using modified steps from different sustainable agriculture studies (FAO, 2014a; Gómez-Limón & Sanchez-Fernandez, 2010; Musumba et al., 2017; Smith et al., 2017; van Loon et al., 2019) while objective 3 was conducted using the RAAIS approach (Schut, Asten, et al., 2016; Schut, Klerkx, Rodenburg, Kayeke, Hinnou, et al., 2015; Schut, Rodenburg, Klerkx, Kayeke, & Ast, 2015). However, data sources from the two procedures complement each other.

3.4.1 Procedure and Techniques for objectives 1 and 2

Objective 1 of the present study is to assess and compare the biophysical characteristics that can determine crop productivity and enable or hinder SI goals/principles for smallholder crop production systems in semi-arid RVB and BVB. Objective 2 assesses and compares smallholder farmers' social and economic characteristics that affect crop productivity and livelihood outcomes, and therefore enable or hinder SI principles in semi-arid RVB and BVB. Mixed methods are adopted to generate qualitative and quantitative data for these objectives. Six steps were followed to define, collect and analyse data. The steps included: (1) indicator selection/validation, (2) data collection, (3) normalisation of data, (4) aggregation into a composite index (approximate continuous variable), (5) calculation of relationships between indicators, and (6) explanations for significant associations. See **Figure 5** below.

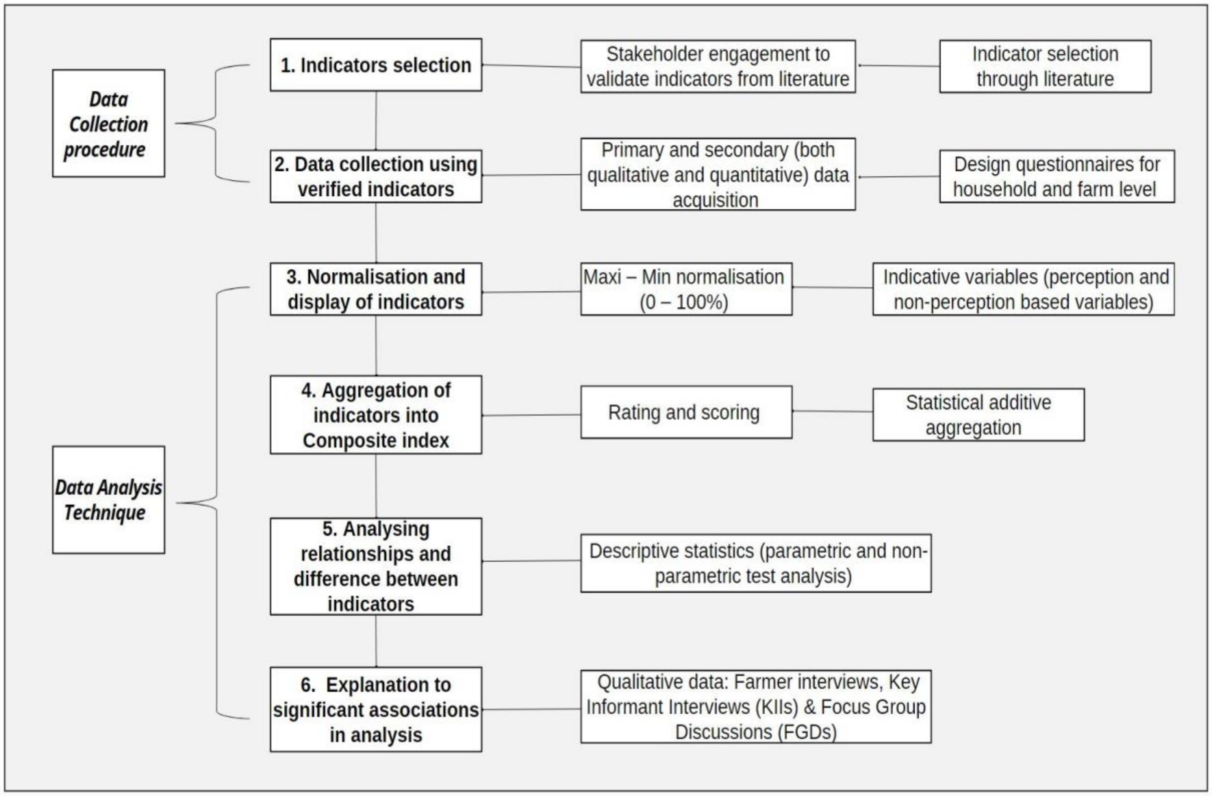

Figure 5*: Showing the SI data collection procedure and analysis techniques used for the present study (Researcher's design).*

3.4.1.1 Population and sampling

Purposive and random sampling techniques were used for collecting data in the RVB and BVB for objectives 1 and 2 of this study. The purposive sampling technique was mainly used to select communities, focus group discussion (FGD) participants, and agricultural experts/stakeholders, while the random sampling technique was used to select the households/farmers within each community for the surveys.

The three target communities in each basin were purposefully selected based on their different levels of access to a permanent surface water source, such as a dam or river. This sampling aimed to examine crop productivity under different water-availability settings within semi-arid river basins in Northern Ghana. The three sampled communities in RVB (Bongo Municipality) include Vea, Beo and Lungu, while the communities in BVB (Lawra Municipality) include Methoh, Zambo and Yagture. The Vea community is closer to the Vea dam in the RVB, while the Beo and Lungu communities are further away. Also, the Methoh community is by the Black Volta River in

BVB, while Zambo and Yagture communities are further away. See **Figure 6** for the map of the study area and **Table 8** for the characteristics of the study communities.

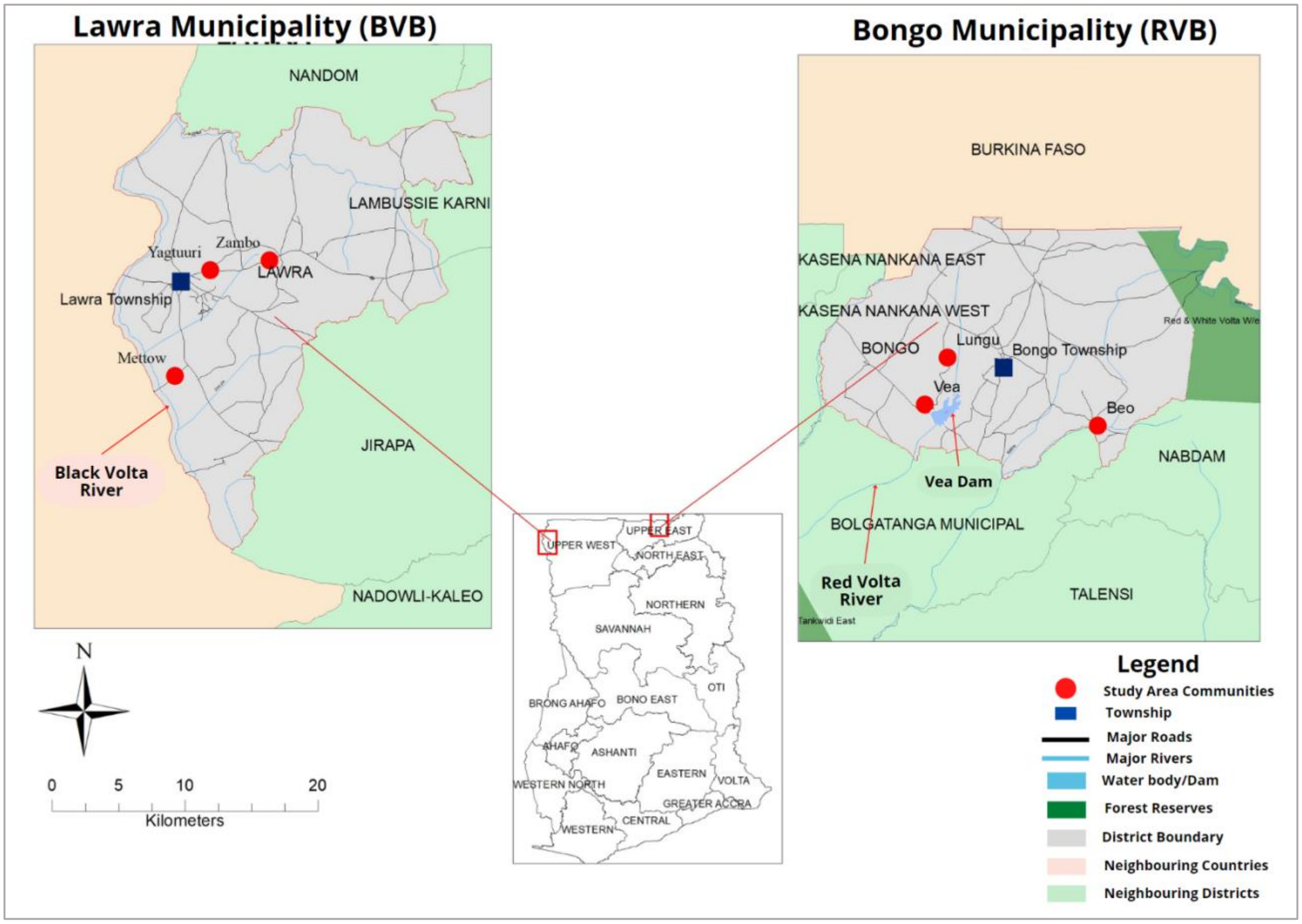

***Figure 6**: The Map of the study area showing the sampled communities in RVB and BVB (developed by the researcher).*

***Table 8**: Showing the characteristics of the study communities in RVB and BVB.*

Characteristics	RVB			BVB		
Community	*Vea*	*Lungu*	*Beo*	*Mettow*	*Zambo*	*Yagturi*
Location	10.87N, -0.85W	10.92N, -0.85W	10.86N, -0.74W	10.65N, -2.9W	10.66N, -2.82W	10.64N, -2.74W
Distance from a permanent water source	0.3*km*	11*km*	22.6*km*	0.25*km*	18.1*km*	26.7*km*
Farming type	Irrigated and rainfed	Rainfed	Rainfed	Irrigated and rainfed	Rainfed	Rainfed
Number of households	272	439	327	181	307	114

Furthermore, the participants selected for the FGDs were based on gendered social groupings. Men and women groups consisting of at least 8 participants were selected for the FGDs in each community within the RVB and BVB. These gendered groupings were necessary due to the patriarchal culture in the study areas and the power dynamics that come with it. Most women do not participate in community meetings; in some cases, women (wives) are not allowed to speak publicly without their husbands' permission. Separating the men from the women was useful for the women to express themselves without intimidation from men, especially their husbands. Also, some agriculture stakeholders, including farmers, were selected for in-depth interviews based on their role within the agriculture system. The stakeholders selected for the key informant interviews (KII) included farmers (male and female, youthful and elderly), experts (NGO and AEAs) and support groups (community leaders and input retailers/suppliers). See **Table 9** below for the design of the purposeful sampling, including communities, farmers, experts, and support groups.

Smallholder households/farmers were randomly sampled as respondents for the survey in RVB and BVB. The surveyed smallholder farmers were household heads or any elderly household member in the absence of the household head. The proportional probability size (PPS) technique (Antwi *et al*., 2015) determined the study population and sample size. According to the 2010 population census, there were 14,537 households representing 95% of households involved in crop production in RVB, while 7,680 households represented 85% of households in BVB. The study sample size was derived based on the above household population in each study area.

The sample size was estimated using the equation below (Antwi *et al*., 2015) at a 95% confidence level with a degree of variability equal to 0.05.

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

Where "n" is the sample size, "N" is the total population size (number of households) for the study areas, and "*e"* is the sampling margin of error, which in this study is equal to 0.05. From the equation, 96 smallholder households/farmers in RVB and 70 in BVB were expected to be randomly selected to constitute the sample size. However, the study increased the sample size to 200 smallholder households/farmers for each basin/district to cover the possible increase in households since the 2010 census and strengthen the sample sizes for the comparative study. **Table 9** below indicates the number of respondents for purposive and random sampling.

Table 9: *The sampling size of FGD, KII and surveys in the RVB and BVB*

Sampling type	*Technique*	*No. of respondents in RVB*				*No. of respondents in BVB*			
		Vea	**Beo**	**Lungu**	**Total**	**Methoh**	**Zambo**	**Yagture**	**Total**
Purposive	**FGD**	24	18	16	58	16	18	22	56
	KII	2	2	2	6	2	2	2	6
Random	**Survey**	57	69	74	200	98	52	50	200

3.4.1.2 Indicator selection and validation

The initial/baseline indicators were identified through a literature review. Existing information from sustainable agriculture and sustainable intensification studies (FAO, 2014a; Gómez-Limón & Sanchez-Fernandez, 2010; Musumba et al., 2017; Smith et al., 2017c; van Loon et al., 2019) was used to select the baseline indicators for the biophysical (objective 1) and socioeconomic (objective 2) domains. SI's environmental/biophysical indicators generally include water, soil, ecosystem (forestry), and crop-health characteristics. These biophysical indicators also describe the risks (such as erratic rainfall, poor soils and deforestation) and strategies (such as fertiliser application and certified seed use) for crop productivity and environmental management at the farm level. The socioeconomic indicators identified in the literature include characteristics related to land use, crop productivity, economic outputs and access to resources. Over 80 indicators were identified across the literature and presented to local stakeholders for review and validation in two workshops in RVB and BVB, as shown in **Table 10** below. Twenty-five (25) stakeholders from different local institutions (formal and informal) were engaged in the validation process.

The validation process began with stakeholders grouping themselves into five groups depending on their expertise. Groups 1 and 2 consisted of experts such as AEAs, some FBO leaders and NGO field officers who are more knowledgeable on biophysical characteristics due to their extension work within communities, as shown in **Table 11** below. Groups 3, 4 and 5 included participants who mostly work with communities to reduce socioeconomic risks such as poverty and lack of access to social, economic and agricultural resources, as shown in **Table 11** below. They include input suppliers/retailers, traditional leaders, civil society groups, NGOs and FBOs. Stakeholders reviewed, discussed and made expert judgements on what indicators to include or exclude based on the context within each basin. The researcher further re-examined the validated indicators to ensure they were measurable.

Table 10: *Showing the biophysical and socioeconomic characteristics selected from literature and presented to local stakeholders in RVB and BVB (See **Appendix E** for more details).*

Biophysical characteristics	***Number of indicators***	***Socioeconomic characteristics***	***Number of indicators***	***Total indicators***
Water-related risk	8	Crop type	2	
Soil-related risk	6	Land tenure	2	
Ecosystem-related	4	Productivity	5	
Crop-related risk	3	Economic	8	
Water-related strategies	6	Food security	3	
Soil-related strategies	6	Asserts	4	
Ecosystem-related strategies	4	Access to input	4	
Crop-related strategies	4	Access to services	5	
		Off-farm activities	2	
		Other factors	5	
Total	**41**		**40**	**81**

Table 11: *Stakeholder groups and their role in biophysical and socioeconomic indicator validation (See **Appendix F(v)** for further details).*

Group	***Stakeholders***	***Validation strength***
Groups 1 and 2	NGO Officers, AEAs, researchers, FBO leaders	Biophysical characteristics
Groups 3, 4 and 5	Input suppliers/retailers, Traditional leaders, civil society groups, NGOs and FBOs	Socioeconomic characteristics

3.4.1.3 Data collection procedure

As described earlier, three data collection techniques, namely surveys, FGDs and KIIs, were used to collect the quantitative and qualitative data sets for these objectives, as shown in **Table 9** above. The procedure included field surveys with prepared questionnaires about the validated indicators and a follow-up with FGDs and KIIs to provide context to some of the outcomes from the survey analysis, as shown in **Table 10** above. The data gathered from the questionnaire included perception and recollection information on the demographic, biophysical and socioeconomic characteristics of farmers in the RVB and BVB. The survey was conducted using a combination of English and the local languages, depending on the respondent's preference.

i. Survey Questionnaires

The demographic data obtained from the surveys in both basins included multiple-choice questions about respondents' community, gender, age, educational level, marital status, size of household, years of farming and farmland size, and land tenure type ***(See Appendix B for details).*** The biophysical data included the Likert scale for constraints/risks assessment and multiple-choice for strategies to manage those risks at the farm level. The Likert Scale assessment for perceived biophysical risks allowed smallholder farmers to rate the observed constraints from 1 to 5 (1 = very low, 2 = low, 3 = Medium, 4 = High, and 5 = Very High). The biophysical constraints/risks under assessment included various indicators related to water, soils, ecosystem and crop health *(See **Appendix B** for details)*. The multiple-choice questions for the on-farm strategies included indicators related to water, soil, ecosystem and crop health management practices. Other follow-up multiple-choice questions included the perceived effectiveness of on-farm strategies, access to expert advisory and the reasons for non-adoption of a strategy. The survey questions for socioeconomic data were related to indicators describing land tenure, crop types, productivity levels, economic outcomes, social activities and access to resources (services and inputs). Multiple-choice questions were designed to collect information on land tenure, social activities and access to resources, while open-ended and Likert scale responses required respondents to state their productivity levels and economic outcomes and compare them to the previous farming seasons *(See **Appendix B** for details)*. Due to the language barrier, two research assistants were recruited at each study site to assist in language interpretation and administer the questionnaires.

ii. Guide for FGDs

Participatory data collection methods like FGDs are very effective in recording farmers' understanding of a biophysical or socioeconomic phenomenon. The FGDs were conducted after the surveys were completed so that some emerging outcomes could be explored in the FGDs. Semi-structured interview guides were used to probe the farmers on key information emerging from the survey that needed clarification or further interrogation. Some of the critical outcomes probed were related to access to resources, migration patterns, perceived challenges in rainfall and alternative sources of income *(See **Appendix C** for details)*. The participatory nature allowed participants to interact and debate some of the survey's emerging outcomes. The main objective of the FGDs is to gain a deeper understanding of the risk, strategies and outcomes of biophysical and socioeconomic domains. The local language was used to conduct FGDs since most participants could not speak English. There were 6 groups (male and female) with at least 8 participants involved in the FGDs in each basin. The data from the FGDs were collected via tape recording, with each session lasting between 90 and 120 minutes. Before recording FGDs and oral interviews, explicit consent was obtained from all participants *(See Appendix C for consent forms)*. Two bilingual agricultural extension officers were hired from both basins to translate “Dagaare” dialogue into English. Following data collection, the researcher diligently transcribed the audio recordings to preserve the cultural nuance of the original language.

iii. Guide for KIIs

The KIIs were conducted with local stakeholders from formal and informal institutions. KIIs also sought to gain in-depth information on the roles these local institutions played, their perceptions of the biophysical and socioeconomic risks and how their institutions have played a role in the agriculture system to improve agriculture and livelihood outcomes for different social groups. The five key local stakeholders and three farmers from each basin were interviewed using semi-structured questionnaires that further probed into respondents' answers for more clarification *(See **Appendix C** for details)*. The local stakeholders interviewed included officials from the District/Municipal department of agriculture (DOA), NGOs such as the centre for indigenous knowledge and organisational development (CIKOD) in BVB and the partnership for rural innovation and sustainable environment (PRISE) in RVB, input suppliers/retailers, and community leaders, including opinion and traditional leaders. The farmers selected for the interviews included a woman farmer, a male farmer and a younger farmer (18 – 39 years) from both basins. These interviews were necessary to provide detailed perspectives that may not be revealed during the survey or FGDs. Except for traditional leaders and farmers in both basins, the interviews were conducted in English as most respondents in these groups were literate. This data was collected via tape recording and written notes. Generally, each interview took between 45 and 90 minutes.

3.4.1.4 Normalisation/display of indicators

Since the agriculture system assessment undertaken was multi-factor, primary data from the surveys come in different unit measurements (Meul et al., 2008). For this reason, a universal measurement is required for some indicators by converting them to a single unit measurement for easy comparison of indicators (Peano et al., 2015).The present study adopts the normalisation method used by Musumba et al. (2017), where visual displays like percentage bar graph are used to display datasets. In the present study, responses from the survey are treated differently based on indicator types and their related unit of measurement. Perception (nominal and ordinal) and actual yield or input (continuous/numerical) datasets were treated and displayed differently. The perception data were collected as close-ended with hierarchical (Likert scale), multiple-choice or binary (Yes/No) responses. These datasets enabled percentages (0% to 100%) to display the perceptions in a simple or 100% stacked bar chart for comparisons between basins. For instance, the perception of indicators related to water, soil, ecosystem and crop health risks were compared between basins using Likert scale results displayed in a 100% stacked bar chart. Multiple-choice response datasets, including crop types, farmland size, migration patterns and FBO membership, were also compared between the two basins using a 100% stacked bar chart. Binary datasets, including adopting appropriate on-farm strategies or access to relevant inputs and services, were also used to compare results between basins using simple percentage bar charts.

The numerical/continuous datasets were displayed using box and whisker plots derived from descriptive statistics, including the number of respondents (N), the mean, standard deviation (SD), the range (minimum and maximum) and the 25th, 50th (median) and 75th percentiles to compare results between the RVB and BVB. The datasets using these descriptive statistics were mostly socioeconomic indicators, including farmland size, crop yields (as well as proportions consumed, sold or used for other purposes), expenditure, incomes, profitability, savings and loans. Finally, some nominal or ordinal datasets about a specific biophysical and socioeconomic theme were also converted to continuous data (dummy variables and approximate continuous variables) to enhance the analysis further. For instance, Likert Scale score is used as continuous data is by calculating the mean score which enable the calculating a summary statistic that can be used in a variety of statistical analyses, such as t-test, correlation and regression (Norman, 2010; Sullivan & Artino, 2013). Binary (dummy) variables represented by 1 or 0, indicating the presence or absence of a category it represents in the observation were created from some categorical data to be included in a regression model. Descriptive tables were also used to display the results of the non-perception/numerical datasets.

3.4.1.5 Rating, scoring and aggregation of indicators

As described earlier, different weighting techniques were applied to different datasets from the survey. In the present study, the normative technique is applied where the subjective weighting was done by experts/stakeholders, including the researcher, during the indicator validation stage, especially for perception-based indicators (FAO, 2014a). The biophysical risk perception data rating was by a Likert scale of 1 to 5, where 1 = Very low, 2 = low, 3 = Medium, 4 = High, and 5 = Very High. To better describe the biophysical risk perception, the analysis further grouped the weighted score of very low and low (1,2) as "Minimum risk", medium (3) as "Moderate risk", and high and very high (4,5) as "Maximum risk". The nominal binary variables, including adopting on-farm strategies, access to inputs and services, FBO membership and migration pattern, were scored using 0 and 1, where 0 represents "No" and 1 represents "Yes". The numerical/continuous datasets are analysed using the relevant metrics, including hectare for farmland size, metric tons per hectare (mt/ha) for yield produced, consumed, sold and for other purposes, Ghana cedis (GH) for savings and loans, and Ghana cedis per hectare (GH/ha) for expenditure, incomes from crop yields as shown in **Table 12** below. The percentiles, especially the median or 50th percentile, were used as the standard to compare the numerical/continuous data between RVB and BVB.

Table 12: *Metrics for numerical dataset (land size, crop yields produced, consumed sold and other purposes, farm expenditure, yield income and profits).*

Indicators	*Field measurement*	*Weighted measurement*	*Formula/Conversion*
• Land size	Acres (ac)	Hectares (ha)	$\frac{1acre}{2{,}471} = 0.405ha$
• Crop yield • Crop yield consumed • Crop yield sold • Crop yield for other purposes	Kilograms per Acres (kg/ac)	Metric tonnes per Hectares (mt/ha)	$\frac{(1kg/1000 = 0.001mt)}{(1ac/2{,}471 = 0.405ha)}$
• Farm Expenditure • Yield income • Yield Profit	Ghana Cedis per Acre (Gh₵/ac)	Ghana cedi per Hectare (Gh₵/ha)	$\frac{1Gh₵}{(1ac/2{,}471 = 0.405ha)}$

Some indicators from the survey with similar weights, scores and descriptions were aggregated into composite indicators, while others were treated as individual indicators. Even though most indicators were analysed individually, the summative technique was used to aggregate some indicators, especially biophysical perceptions, into sub-components related to water, soils, ecosystem and crops risks and strategies (FAO, 2014a; Meul et al., 2008; N. Sabiha et al., 2016). Numerical data were analysed as individual indicators, especially socioeconomic indicators such as yields produced, consumed, sold, and for other purposes, expenditure, incomes, loans, savings, remittances, and alternative income sources. Musumba et al. (2017) argue that assessing individual indicators may provide a detailed description of the agriculture system that can be useful for targeted interventions.

3.4.1.6 Assessing indicator relationships and differences between basins

The Statistical Package for the Social Sciences (SPSS) version 28 is the analytical software used for conducting parametric and non-parametric tests to explore associations, relationships and differences within the datasets and compare them between and within basins. The parametric test analysis included simple linear regression, multiple linear regression, logistic regression, pair-wise regression and Pearson's t-test. The non-parametric tests include Pearson's chi-square (χ^2), Spearman's correlation (*r*), Mann-Whitney U, and Kruskal Wallis H. The outcomes from the test analysis with a significance level or p-value ≤ 0.05 were considered to be statistically significant. The $p \leq 0.05$ was used as a cut-off point because it is often the most acceptable and widely used significant level among the statistical community (Collis & Hussey, 2014). However, p-values $\geq$ 0.05 may be used as a reference or in comparison to a significant p-value. The type of association, the questions asked from the dataset and the test conducted for the quantitative analysis are displayed in **Table 13** below (see ***Appendix D*** for all tests and questions asked in the study for Objectives 1 and 2).

Table 13: *Showing the statistical test conducted, how they were used, and sample research questions asked from the data for Objectives 1 and 2.*

Tests	How it was used	*Example of research questions tested*
Simple linear regression (SLR)	SLR was used to predict the value of a dependent variable based on the value of one independent variable. For instance, respondents expected yield/ha was used as an independent variable to predict the value of actual yields/ha. Also, the simple linear regression tested whether respondents' expenditure could predict their expected yield/ha.	• *Can respondents' total actual yield/ha levels determine yield/ha levels consumed and sold within basins?* • *Can the total farm expenditure determine respondents' expected and actual yield/ha levels within basins?*
Multiple linear regression (MLR)	MLR was used to predict the importance of more than one independent variable on a dependent variable. For instance, multiple linear regression analysis was conducted to identify the importance of farm size, yields, expenditure, and agriculture inputs and services on respondents' biophysical risk perceptions.	• *Can respondents' biophysical risk perceptions be predicted by their farm size, expected yields/ha, expenditure, inputs and services within basins?*
Stepwise regression	Stepwise regression was used to predict the most relevant independent variables on a dependent variable by adding and removing independent variables based on their significance. For instance, stepwise regression was used to identify which on-farm strategies are relevant for crop yields.	• *Which adopted on-farm strategies could better influence crop yield levels within basins?* • *Which farm inputs or services could better influence expected and actual crop yield/ha levels within basins?*
Logistic regression	Binary logistic regression was used to identify the relationship between one or more independent variables and a binary dependent variable (categorical variable). For instance, each of the respondents' biophysical risk perceptions was used as an independent variable in a binary logistic regression model to their adoption of the on-farm strategy.	• *Which relevant biophysical risk perceptions could better predict adopted on-farm strategies within basins?* • *Can access to agriculture extension influence access to information in RVB and BVB?*
Spearman's Correlation (r)	Spearman's r was useful for identifying the strength of the relationships between 2 or more non-parametric datasets such as respondents' savings and loans, household size and crop yields, alternative sources and incomes, crop yields and expenditure, and the number of on-farm strategies adopted and crop yields.	• *Does farm expenditure increase or decrease with crop yield/ha consumed and sold within basins?* • *Does the total cropland size increase or decrease with household size within basins?*
Pearson's Correlation (r)	Pearson's r was used to establish the strength of the relationship between parametric data, such as respondents' overall perception of biophysical risks and the number of on-farm strategies adopted.	• *Does the number of adopted on-farm strategies increases or decrease with the biophysical risk perceptions within basins?*

Chi-square (X^2) test	Pearson's chi-square test was used to determine whether there is a significant difference between the expected and observed frequencies in one or more categorical variables. For instance, Pearson's chi-square was used to test whether the frequency of adopted on-farm strategies differs from perceived biophysical risks in RVB and BVB.	• *Is the pattern of adopted on-farm strategies different based on biophysical risk perceptions within basins?* • *Are the cropland sizes for primary or secondary crops different between basins?*
Pearson's t-test	Pearson's t-test was used to determine whether a significant difference exists between the means of two independent samples/ groups that are normally distributed. For instance, Pearson's t-test was used to determine whether there are differences in water, soil, ecosystem and crop health-related risk perceptions between RVB and BVB.	• *Are the perceived water, soil, ecosystem, or crop health-related risks different or similar between basins?* • *Is the perceived effectiveness of on-farm strategies different or similar between basins?*
Kruskal-Wallis H test	The Kruskal-Wallis H was used to determine whether there is a significant difference in the population medians among two or more independent groups. For instance, total crop yield levels (actual and expected) differ within communities in RVB and BVB.	• *Are the expected and actual crop yield/ha levels different for communities within basins?*
Mann-Whitney U test	Mann-Whitney U test was used to determine whether there is a significant difference between the medians of two independent samples/ groups that are not normally distributed. For instance, the Mann-Whitney U was used to determine whether the actual crop yield levels differ between RVB and BVB.	• *Are basins' expected primary and secondary crop yield/ha levels different?* • *Are the amounts spent (GH/ha) on crop production different between basins?*

3.4.1.7 Explanation of significant associations found in the statistical analysis

Secondary and primary data were used to provide explanations and context to some of the significant outcomes from the quantitative analysis. Quantitative data from secondary sources, including the Municipal/district DOA, Ghana Statistical Service (GSS) and other relevant documents, were used to further explain or contextualise the findings from objectives 1 and 2. For instance, rainfall and crop production data obtained from the DOA in the RVB and BVB helped understand the outcomes from the perception responses on biophysical risks such as erratic rainfall, dry spells, poor soils and pest infestation. Qualitative data obtained from the FGDs and KIIs were also useful for providing detailed explanations of specific outcomes that the quantitative data sources could not fully explain. For instance, FGDs with women groups helped understand communities' traditional and cultural foundations that affect land tenure arrangements for women farmers more than their male counterparts. Also, KIIs with stakeholders such as extension agents explained why some social groups within the same basin adopt more on-farm strategies and technologies than others.

3.4.2 Procedure and Techniques for Objective 3

Objective 3 aims to investigate and compare the institutional constraints and entry points for implementing SI within smallholder crop production systems in semi-arid RVB and BVB. The

Rapid Appraisal of Agricultural Innovation Systems (RAAIS) methodology was adopted for this objective. The RAAIS is a participatory stakeholder engagement approach that includes workshops, interviews and surveys (when necessary) with relevant stakeholders to understand the challenges institutions face in supporting the development of innovative agriculture within an agriculture system. The RAAIS provides holistic and multi-level perspectives with diverse stakeholder groups using quantitative and qualitative processes to analyse and provide innovative solutions for agriculture development (Schut, Klerkx, Rodenburg, Kayeke, Hinnou, et al., 2015; Schut, Rodenburg, Klerkx, Kayeke, van Ast, et al., 2015). This methodology was previously used in Central African Highland countries (Burundi, Rwanda and Central African Republic) to assess sustainable agriculture's institutional constraints and entry points in natural resources management. The methodology was adopted for the present study because it was easy to replicate and useful for conducting participatory research that can enable local stakeholders/institutions to identify their constraints and capacities to support the implementation of SI in Northern Ghana's semi-arid agriculture system.

3.4.2.1 Sampling procedure

The researcher worked with experts from the DOA in BVB in Upper West (Lawra Municipality) and RVB in the Upper East region (Bongo District) to select key stakeholders/participants from relevant local institutions. The team used two weeks to engage stakeholders and their respective institutions with invitation letters, in-person visits and phone calls as part of the pre-workshop activities. Stakeholders were informed about their roles at the workshops and the preparations required to participate in the activities. Key stakeholders from 5 formal and informal institutions, including leaders from farmer-based organisations (FBOs), extension agents (EA) from Municipal/Districts' DOA (Government), community leaders (Traditional authority/opinion leaders), input suppliers (Private sector) and technical officers from non-governmental organisations (NGOs) were nominated to participate. Twenty-five participants were present for each workshop in both basins *(See **Appendix F(v)** for more details)*. The stakeholder engagements were held in RVB on December 20th and 21st, 2019, and from January 15th to 16th, 2020, in BVB.

3.4.2.2 Data collection and analysis

The data collection and analysis were co-produced with stakeholders as part of the RAAIS methodology. The process includes identifying constraints, categorising constraints and identifying entry points for implementing SI. Stakeholders were asked to think about the five most important constraints that affect their work within their institutions. **Table 14** below shows the steps for the participatory data collection and analysis.

Table 14: *Participatory data collection and analysis of stakeholder constraints, SI innovation entry points, and strategies in the RVB and BVB.*

Procedure		Sessions	Activities	Objectives
Identifying constraint	1.	*Opening and participant introduction*	Participants (1) introduce themselves and receive information about the workshop methodology; and (2) are subdivided over different stakeholder groups (e.g., farmers, NGO, private sector (input suppliers), government (AEA), community leaders	• To ensure an equal representation of participants over the different stakeholder groups
	2.	*Individual brainstorming about constraints*	Participants (1) individually identify 5 constraints they face in their work	• To make an inventory of general constraints within the agricultural system faced by stakeholders
	3.	*Developing a top-5 of constraints in Stakeholder groups*	Participants (1) discuss constraints within their respective stakeholder group; (2) develop a stakeholder group top-5 of constraints; (3) present the top-5 to other stakeholder groups; and (4) discuss within and between stakeholder group(s)	• To gain insights into the key constraints in the agricultural system as faced by different stakeholder groups • To create awareness and stimulate learning among stakeholders
Categorising constraints	4.	*Categorising Constraints along different types of institutions*	Participants (1) categorise top-5 constraints as policy, research, education and training, extension, markets and/or politics-related; (2) present results to the other groups; and (3) discuss within and between the stakeholder group(s)	• To gain insights into how key constraints relate to the different types of institutions (institutional subsystem) • To create awareness and stimulate learning between stakeholders
	5.	*Categorising Constraints along different Governance dimensions*	Participants (1) categorise top-5 constraints under Accountability, stability, effectiveness, the rule of law, and corruption, (2) present results to the other groups; and (3) discuss within and between the stakeholder group(s)	• To gain insights into how key constraints relate to the different governance dimensions. • To create awareness and stimulate learning between stakeholders
	6.	*Categorising constraints along structural conditions that can enable or constrain innovation/SI*	Participants (1) categories top-5 constraints along infrastructure and asserts, institutions, interactions and collaborations, and capacities; and (2) discuss within and between the stakeholder group(s)	• To gain insights into how the stakeholder constraints relate to structural conditions provided agricultural innovation/SI support systems and whether these enable or constrain innovation capacity • To create awareness and stimulate learning between stakeholders
	7.	*Categorising constraints across different(administrative) levels within the institutional subsystems*	Participants (1) categorise top-5 constraints across community/local, district, regional and national; (2) discuss results with other stakeholder groups; and (3) discuss within and between the stakeholder group(s)	• To gain insights into how key constraints relate to different institutional (administrative) levels • To identify and analyse interactions between different levels • To create awareness and stimulate learning between stakeholders
	8.	*Identifying relationships between constraints, and identifying key constraints*	Participants (1) jointly discuss and identify relations between the different constraints; (2) identify constraints or challenges that are central in the analysis, and (3) discuss within and between the stakeholder group(s)	• To analyse relationships between different constraints • To identify key constraints • To create awareness and stimulate learning between stakeholders • Identify generic entry points for enhancing the innovation/SI capacity in the agricultural system

Exploring entry points for innovation/SI	9.	*Exploring constraints stakeholder groups can solve themselves versus problems that can only be solved with or by others*	Participants (1) categorise top-5 constraints as: 'can be solved within the stakeholder group', or 'can only be solved in collaboration with other stakeholder groups; and (2) discussion within and between the stakeholder group(s)	• To identify constraints that require collaboration between stakeholder groups • To create awareness and stimulate learning between stakeholders • Identify entry points for innovation/SI in the agricultural system
	10.	*Exploring constraints that are easy/ difficult to solve*	Participants: (1) categorise top-5 constraints as relatively 'easy' or 'difficult' to address; and (2) discuss within and between the stakeholder group(s)	• To explore which constraints require system optimisation (easy to address) and those that require system transformation (difficult to address) • To create awareness and stimulate learning between stakeholders • To triangulate data with Session 8 (are key constraints perceived to be easy/ difficult to address) • Identify entry points for enhancing the innovation/SI capacity in the agricultural system
	11.	*Exploring constraints that are structural/ operational*	Participants categorise top-5 constraints along a four-step gradient, ranging from 'very structural', 'structural', 'operational' and 'very operational' challenges and constraints	• To distinguish between structural constraints that require specific SI innovation and more structural problems that require generic innovation. • To create awareness and stimulate learning between stakeholders • To triangulate data with Sessions 8 and 10 (relation between key constraints how stakeholders perceive these) • Identify generic entry points for enhancing the innovation capacity in the agricultural system
	12.	*Identifying priorities and solution strategies*	Participants (1) jointly discuss and develop an overall top-5 of constraints; and (2) jointly identify potential strategies to address these constraints	• To explore opportunities for addressing systems constraints through multi-stakeholder collaboration • To explore similarities and differences with the key system's constraints identified in Session 8 • Identify key entry points for innovation
	13.	*Identifying timeframes for implementing solutions*	Participants jointly group strategies to address these constraints under "Short term ($\leq$1 year); middle term (1–5 years); long term (5–10 years)	• To identify the timeframe to which solutions to constraints can be implemented. • Triangulate sessions 8,10 and 11 related to solutions with timeframe

3.4.2.3 Follow up KIIs

The participatory stakeholder activities were followed up with KIIs of relevant stakeholders. One member of each institutional stakeholder group was selected and followed up for further details and clarification on the emerging outcomes of the study. These KIIs were conducted about 10 months after the workshops were conducted. The follow-up time frame helped the study share the workshop outcomes with stakeholders/institutions and let the researcher receive feedback on whether their constraints have changed or been complicated by other phenomena since the workshop. Each KII took about 30 to 90 minutes and was recorded and transcribed in English. ***See Appendix C*** for the KII guide.

3.5 Ethical consideration

The study's ethical clearance was submitted and approved by the University of Cape Town Faculty of Science on October 8th, 2019 (*See **Appendix A** for the approved letter)*. All protocols and procedures needed for the study's ethical success were followed and observed throughout the data collection phase. In the study areas, protocols were followed for community entry with verbal and written permissions from community leaders, including chiefs, individuals from relevant agencies or organisations, assemblypersons, and others in authority. The community entry in BVB was easier than RVB due to the researcher's prior engagement with stakeholders in the area as a technical officer for a climate change adaptation project.

The ethical process for all data collection began with informing all respondents about the study's purpose to get their verbal consent before the survey, workshop or interview. Any actions that might expose respondents to physical and psychological threats were mitigated or avoided. For instance, women's FDGs were conducted separately from the men for the women to freely express their opinions without intimidation from their male counterparts which is often the case in most communities in both basins. Participation in the data collection process was voluntary, and respondents were encouraged but not compelled to participate. No justification was needed if a respondent decided to quit their participation in the middle of the survey, workshop or interview. Even though a few of the respondents could not answer all questions, especially from the surveys, none declined their participation.

Respondents were assured that the safety and confidentiality of the information provided for the study would be handled properly, as the data collected were meant only for academic purposes. To ensure confidentiality, respondents' identities were anonymised with codes such as BVB001 to indicate the first respondent in BVB. No personal information (including name, address, phone records, email address, social security number, national identification number, driver's licence number, or criminal and medical records) was taken. All collected data (documents, photos, recordings and videos) are securely stored in the UCT Microsoft OneDrive cloud services and duplicated in the UCT google drive.

3.6 Limitations of the study methodology

Even though the research design and the methodological approach adopted for the study were carefully designed to address the research questions, they came with some limitations. These limitations may be through biases from the primary data, extreme cases or outliers from data, overlapping frameworks, oversimplified secondary data sources, and time/funding limitations.

The biases in primary data were related to site selection, timelines and research assistance. The case study site in BVB was selected due to the researcher's familiarity, as he had previously worked with local stakeholders in the area. This bias was reduced by selecting other case sites (RVB) unfamiliar to the researcher for comparison. Due to the short data collection procedure, some respondents had less time to respond to the survey questions, which may affect their detailed recollection of events. Respondents were encouraged to skip answering questions they could not immediately recall to reduce incorrect or incomplete responses. Also, some research assistants were extension officers with biases in administering the survey questions in favour of their work with farmers. This bias was reduced with the researcher's thorough supervision and the clear understanding that the research was meant for academic purposes, not an evaluation of their work.

Moreover, some of the primary data from the survey, especially the continuous data, were extreme outliers that could have affected the true outcomes of the study. Some extreme outliers may have been typographical, or imputation errors identified with box and whisker plots in SPSS. Removing and normalising outliers from the data helped reduce this limitation and ensure quality control throughout the study.

The primary data from surveys, interviews, stakeholder engagements and discussions may be subjective opinions or perceptions of respondents/participants, which may oversimplify the actual reality. However, using qualitative data from KIIs, FGDs and workshop discussions provided more context to the quantitative data from the survey and vice versa. The combination of different data types validates each other, reducing the subjective biases within the data.

Furthermore, the study's conceptual framework of integrating biophysical, socioeconomic and institutional factors presented a methodological challenge of producing a unified methodological approach to analyse the data. Nevertheless, analysing the individual objectives with dynamic data collection procedures enabled an independent yet integrated analysis where data from one objective provides a context for another. Also, the secondary data such as the rainfall, crop yield levels and soil sample data obtained from institutional reports and literature may have been oversimplified at the basin/district level, which may not fully reflect actual results within the sampled communities. The study tried to reduce this limitation by crosschecking the secondary data with multiple sources. However, this limitation could have been better resolved with enough time and funding to carry out a medium to short-term longitudinal data collection for biophysical and socioeconomic data, including rainfall, soil sample, crop yields and incomes.

3.7 Summary

This chapter focused on the methodological approach for assessing the biophysical, socioeconomic and institutional indicators for achieving SI in the RVB and BVB. The methods section described the conceptual framework of sustainability domains, principles and indicators for contextualising SI within the case study areas. The research design followed the onion model, which describes the research's philosophy, approach, strategy, time horizon and techniques/procedures. The techniques/procedures for data collection and analysis were organised based on the study's objectives. The data collection and analysis techniques used for Objectives one and two were adopted from several methods used in assessing sustainable agriculture systems, primarily based on quantitative surveys and supplemented by qualitative KIIs and FGDs. The RAAIS methodology, primarily a participatory and qualitative data collection procedure, was used to collect and analyse institutional constraints, entry points and strategies for SI in Objective 3 of the study. Finally, the chapter describes the ethical processes followed in undertaking primary research with human subjects at the local level and provides the study's limitations, including how they were mitigated to enhance the reliability and confidence of the findings. The next chapter discusses the case study areas, indicators /variables and demographic characteristics of respondents.

CHAPTER 4

CHARACTERISTICS OF THE STUDY AREA, RESPONDENTS' DEMOGRAPHIC BACKGROUND AND INDICATOR VALIDATION FOR SI

4.1 Introduction

This PhD aims to determine the factors contributing to productivity differences between RVB and BVB and how these factors could influence the implementation of SI within smallholder agriculture systems in semi-arid Northern Ghana. The study's objectives are to assess and compare the biophysical, socioeconomic and institutional characteristics of the smallholder agriculture system that could hinder or enable SI in Northern Ghana. This chapter provides the background context to the study area, the characteristics of the respondents surveyed and the approved indicators for the quantitative survey.

4.2 Study Area

The study area describes the research locations' characteristics, including the specific site location, the map of the study area, physical characteristics, socioeconomic characteristics, and administrative or institutional characteristics.

4.2.1 Site selection

Based on the aim of the study, which sought to understand the productivity differences between BVB and RVB, the study considered semi-arid areas of Northern Ghana as the main criteria for selecting a comparative study site. Other criteria include permanent water sources (river/dam), transboundary river basin (sharing borders with Burkina Faso), area size, and population size. The river basins in semi-arid areas of Northern Ghana that met these criteria for the comparison were BVB and RVB. See **Table 15** and **Figure 6** below.

RVB is located within the Bongo municipality in the Upper East region of Ghana. The Bongo district shares borders with Burkina Faso to the North, Kassina-Nankana district to the East, Bolgatanga municipality to the South-west, and Nabdam district to the South-east. The district has a total land area of 425 km^2, between latitude 10.50^o - 11.09^o N and longitude 0.45^o W. The district's population density is about 283 per km^2, and the average household size is six persons per household (GSS, 2021). There are about 38 communities in the district, and the study used three communities representing locations relative to the primary and permanent water source (Vea dam). These communities include the Vea Community, closer to the Vea dam and the Lungu and Beo communities, further away from the dam.

BVB is within the Lawra and Nandom municipalities in the Upper West region of Ghana. Until 2014, the Nandom and Lawra municipalities were one district. For the study, we used the Lawra municipality as the main study site since it had longer secondary records we could use as part of the study. The Lawra Municipality is at the north-western corner of the Upper West region where Burkina Faso borders it to the West, Nandom municipality to the North and Jirapa Municipality to the South-East. The Lawra municipality covers 514 km^2 and lies between latitude 10.35^o – 10.40^o N and longitude 2.50^o – 2.53^o W. The recorded population density is about 114 per $km^{2,}$ and the average household size is about four persons per household (GSS, 2021). About 50 communities are within the municipality, and the study used three communities representing locations at different distances from the primary and permanent water source (Black Volta River). These communities include the Mettow Community by the BVB River and the Zambo and Yagture communities further away from the dam.

Table 15: *Showing the regions, locations, area sizes, population densities and the number of communities in RVB and BVB. (Source: GSS, 2014a; GSS, 2014b)*

Characteristics	RVB	BVB
Region	Upper East	Upper West
Location	10.50N - 11.09N, -0.45W	10.35 - 10.40N, 2.50 - 2.53W
Area size	425 km^2	514 km^2
Total Population	120,254	58,433
Population density	283 per km^2	114 per km^2
Average household size	6 persons	4 persons
Number of communities	38	50

4.2.2 Physical characteristics

The physical characteristics of the study sites include the climate, vegetation, soils, relief and drainage. The Bongo district has unimodal rainfall with an average of about 70 rainy days (from April to October) ranging between 600mm to 1400mm yearly (GSS, 2014a). The average monthly temperature in the district is about 21^oC. Temperatures range from 40^oC maximum just before the rainy season in December to about 12^oC minimum during the peak of the dry season in Jun/July (GSS, 2014a). Due to the district's climatic conditions, longer dry seasons often occur, which dry and wither the vegetation before the onset of rains. Except for the Vea dam, other drainage systems in the district, including small rivers and dugouts, dries up a few months after the rainy season, which prevents some farmers from practicing dry-season farming. The soils are mostly coarse sandy loam and coarse clay loam developed from decomposed granites (GSS, 2014a). The high population density and intensive nature of the agriculture system in the Bongo district are contributing to increasing land degradation, soil exhaustion and erosion.

The Lawra municipality has unimodal rainfall, with a minimum temperature of 22°C at night and a maximum of 35°C throughout the year. The highest monthly temperatures rise to 39°C in May, just before the onset of rains, while the lowest temperatures could go below 16°C during the peak of the dry season in December when the Sahara winds dry up the vegetation (Lente, 2017). Rainfall ranges between 840mm and 1400mm and is likely to occur between April and October when the Tropical Maritime airmass blows across the district. However, rainfall has been erratic, with early or late onset than expected. A prolonged dry season causes dry vegetation, often prone to bushfires. However, besides shrubs affected by bushfires, prominent trees such as shea, dawadawa, and baobab are fire-resistant (GSS, 2014b). The primary drainage system in the area is the Black Volta River, located at the district's western border and serves as a boundary between Ghana and Burkina Faso. The smaller tributaries from the Black Volta River dry up during the dry season even though groundwater could be explored for irrigation in communities further away from the river. Generally, the soils are laterites developed from Birimian and granites (GSS, 2014b). Alluvial and sandy loam soils are found along the Black Volta River and its tributaries. Land use practices coupled with the poor nature of soils in most locations in the district's farming activities.

Table 16: *Showing physical characteristics of the study areas in RVB and BVB. (Source: GSS, 2014a; GSS, 2014b)*

Characteristics	**RVB**	**BVB**
Rainfall type	Unimodal	Unimodal
Rainfall amount (average)	600*mm* - 1400*mm*	840*mm* - 1400*mm*
Temperature range (average)	21°C *(mini)* - 40°C *(max)*	22° C *(mini)* - 39° C *(max)*
Soil type	Sandy loam and course clay loam	Sandy loam
Vegetation	Sahel and Sudan-Savannah with fire-swept grassland and deciduous trees	Guinea savanna grassland with medium size trees
Relief	90*m* - 300*m* above sea level	180*m* - 300*m* above sea level
Geology	Granite and Birimian rocks	Birimian and granite rocks
Drainage	Red Volta basin with Vea dam as the main water source	Black Volta River is the main water source

4.2.3 Socioeconomic characteristics

The socioeconomic activities in the study sites generally centre around sociocultural norms, livelihood activities, and infrastructure. Two main ethnicities in the Bongo district, the Bossis and Gurunsis, comprise over 90% of the population. The major languages in the Bongo district include Bonni and Guruni, spoken by the Bossis and Gurunsis, respectively. Most surveys were conducted in these languages. Traditional authorities such as the Chiefs, Queen Mothers and Tindaanas in the area exert power over the communities and control the access and use of lands and other natural resources. However, there is one paramount Chief given the authority by other traditional leaders to oversee the activities of the traditional area. The district's traditional area has one festival called "Azambene", which means the fire festival, which all ethnic groups celebrate to than their ancestors for a good harvest. Agriculture is the primary economic activity for more than 72% of the population, while services and manufacturing employ the rest. The principal agriculture activity for most farmers in ensuring household food security and income-generating is crop production, followed by small ruminants and poultry. Manufacturing activities include food processing such as oil extraction, shea butter processing, pito (local beer), and handicraft, including weaving local textiles and basketry. Furthermore, most of the roads linking communities in the district are feeder roads, and most of the population lives in mud houses with straw or zinc roofing. There are about 70 primary and basic schools, only three public senior high schools and no tertiary or vocational schools.

In the Lawra Municipality, the dominant ethnic group are the Dagaatis, who speak Dagaari as the main local language. Most of the surveys were conducted in Dagaari. The municipality has a strong traditional authority presence with one paramount Chief, eight divisional chiefs, sixteen sub-chiefs, and 32 headsmen/Tindaanas who control land and other natural resources. All communities in the municipality celebrate the Kobine festival, representing a good harvest and thanksgiving season. Agriculture is the major livelihood activity supporting about 78% of the population, with manufacturing and services supporting 22%. Crop production is mainly subsistence, with some cash crops and animal production supplementing incomes. Most of the manufacturing services within the municipality are agro-based, such as shea butter, groundnut processing, and pito brewing. Other manufacturing activities include carpentry, blacksmithing, welding, and vulcanising. The Lawra municipality has four vocational, technical and nursing training schools that supply the district and other districts with skilled labour for the services and manufacturing sector. One asphalt road links the municipality to Burkina Faso, and several feeder roads link communities.

Table 17: *Showing socioeconomic characteristics of the study areas in RVB and BVB. (Source: GSS, 2014a; GSS, 2014b)*

Characteristics	RVB	BVB
Ethnic groups	Bossis and Gurunsis	Dagaatis
Primary occupation	Agriculture (70% of the population)	Agriculture (78% of the population)
Agriculture type	Subsistence crop production, ruminant rearing, and poultry farming	Subsistence crop production, with some cash crops and animal production
Off-farm activities	Oil extraction, shea butter processing and pito (local beer) and handicraft (basketry)	Shea butter, groundnut processing, pito brewing, carpentry, blacksmithing, welding, and vulcanising
Language	Bonni and Guruni	Dagaari
Education	70 primary and basic schools, 3 public senior high schools and no tertiary or vocational school	30 primary and basic schools, 3 senior high schools and 4 tertiary schools (vocational, technical, and nursing training)
Infrastructure	Several feeder roads linking communities, and most of the population lives in mud houses with straw or zinc roofing	One asphalt road links the municipality to Burkina Faso, and several feeder roads link communities

4.2.4 Administrative/Institutional Characteristics

This study's administrative/institutional characteristics describe the public/government and private structures and activities supporting the Bongo district's agriculture system and Lawra municipality. The public administrative/institutional structures in the Bongo district and Lawra municipality are similar due to the decentralised nature of the governance system in Ghana. National-level administrative power and resources are decentralised to districts and municipal assemblies to implement local-level actions (Padgham et al., 2015). The local-level public institution responsible for enhancing agriculture is the DOA and the Ghana Irrigation Development Authority (GIDA). However, due to resource constraints and the scope of work, GIDA operates from the regional level and provides training and technical support to DOA when needed. The Department of Planning (DOP), Department of Information (DOI) and the Department of Gender and Social Welfare (GSW) at the local level often collaborate with the DOA to support farmers or enhance their capacity to boost agriculture at the local level.

The non-governmental administrative/institutional structures that support agricultural productivity include community leaders (such as the Traditional Authority), FBOs, NGOs, and input dealers/retailers. These institutions are recognised as relevant stakeholders within the agriculture system responsible for supporting smallholder farmers with inputs and services to supplement the activities of the public institutions.

4.3 Biographic characteristics of surveyed farmers in the Study sites

The section compares respondents' community, gender, age, educational level, marital status, household size, household status, occupation, cropland size, and land ownership in RVB and BVB. See **Table 18** below.

Table 18*: Showing the household head's characteristics in percentages for communities within RVB and BVB. (Source: Field survey, 2020, 2021).*

Household Characteristics	Red Volta basin (RVB)				Black Volta basin (BVB)			
	Vea (n = 57)	*Beo (n = 69)*	*Lungu (n = 74)*	*Total (n = 200)*	*Methoh (n = 98)*	*Zambo (n = 52)*	*Yagtuure (n = 50)*	*Total (n = 200)*
	%	%	%	%	%	%	%	%
Gender								
Male	65	55	55	*58*	56	59	62	*59*
Female	35	45	45	*42*	44	41	38	*41*
Age								
< 20yrs	2	-	-	*1*	6	7	6	*7*
20 – 29yrs	17	8	10	*11*	15	24	18	*20*
30 – 39yrs	30	23	19	*24*	23	29	20	*25*
40 – 49yrs	39	37	28	*34*	23	18	25	*21*
≥ 50yrs	12	32	44	*30*	33	22	30	*27*
Marital Status								
Single	14	7	6	*9*	12	13	18	*14*
Married	81	80	81	*80*	67	76	74	*73*
Divorced/separated	-	1	1	*1*	6	1	2	*3*
Widowed	5	12	12	*10*	15	10	6	*11*
Educational level								
Primary	23	16	7	*15*	15	7	10	*10*
JSS/Middle Sch.	30	27	20	*26*	15	18	28	*20*
Non-formal education	14	19	13	*16*	2	6	6	*5*
Sec./Voc./Tech.	9	3	4	*5*	4	8	4	*6*
Tertiary	4	3	9	*5*	10	3	4	*5*
None	21	32	46	*34*	54	57	48	*54*
Household status								
Head	48	58	58	*55*	73	60	64	*64*
Member	52	43	42	*45*	27	40	36	*36*
Occupation								
Farming	86	96	96	*93*	92	98	96	*96*
Formal employ.	2	3	4	*3*	4	1	2	*2*
Petty trading	4	-	-	*1*	2	1	-	*1*
Labour Work	7	1	-	*3*	-	-	2	*1*
other	2	-	-	*1*	2	-	-	*1*
Household size								
0 - 5	18	15	26	*20*	50	45	54	*49*
6 - 10	63	61	51	*58*	35	46	38	*41*
11+	20	24	23	*23*	15	9	8	*11*
Years of farming								
< 2yrs	2	-	-	*1*	12	3	2	*5*
2-5yrs	14	1	4	*6*	10	15	30	*18*
6-10yrs	28	11	7	*15*	14	11	14	*13*
11-15yrs	12	5	1	*6*	12	15	10	*13*
≥ 16yrs	44	82	87	*73*	54	55	44	*52*

Respondents' demographic information enabled the study to analyse and understand the characteristics influencing biophysical and socioeconomic outcomes within the case study sites.

4.3.1 Biographic information of respondents

4.3.1.1 Gender

The study surveyed almost the same number of male and female respondents in RVB and BVB. The results indicate 58% male and 42% female respondents surveyed in RVB compared to 59% male and 41% female respondents in BVB. The gender composition of the surveyed farmers at the community level reflects the overall percentages in RVB and BVB. The survey showed that more than one-third of respondents selected through random sampling were females, and less than two-thirds were males. However, the 2021 census report shows that in the Bongo district and the Lawra municipality, there are more females (about 53%) than males (about 47%) composition in the household (GSS, 2021). The possible reason why the number of surveyed farmers favour more males than females is due to the study targeting household heads than members. Traditionally, men are considered family heads rather than women. Wives may assume the head of the household when the husband has passed away or permanently migrated (Lente, 2017).

4.3.1.2 Age group

The age group of respondents in BVB are younger than those in RVB. The results show that 64% of respondents surveyed in RVB were ≥ 40 years old, and 36% were < 40 years old, compared to BVB, where 52% of respondents were < 40 years old, and 48% were ≥ 40 years old. Also, more respondents from the Lungu community in RVB are elderly than other communities, especially the Vea community. Generally, the 2021 census report shows that the age composition of the household population is youthful in both RVB and BVB. The possible reason for the elderly composition of the surveyed respondents could be the migration of youth at the time of the survey. Young people in Northern Ghana often migrate to other places, especially cities in Southern Ghana, during the dry season (Lawson et al., 2020; Nyantakyi-Frimpong & Bezner-Kerr, 2015). However, elderly farmers have longer migration histories or experiences than younger farmers (GSS, 2014b, 2014a).

4.3.1.3 Marital status

More respondents in RVB and BVB are married than unmarried (single, widowed and divorced/separated). In RVB, 80% are married, and 20% are unmarried, while in BVB, 73% of married respondents are more than 27% unmarried. A possible reason for the higher percentage of married respondents in both basins is that the study targeted households rather than non-household respondents. Most Northern Ghana households consist of nuclear families (husband, wife and children) and extended family living together within a compound house, while other types of household structure may include a single parent (widowed or divorced) with no spouse or nuclear family without children (GSS, 2014a)

4.3.1.4 Educational status

The survey shows that the literacy/education rate in RVB is higher than that of BVB. About 66% of respondents in RVB have at least basic school education, while 34% do not have any education. On the contrary, in BVB, 54% of respondents do not have any form of education compared to the 46% of educated respondents. The population census data shows that the educated or literate population in RVB (48%) is higher than that of BVB (45%), even though they are below 50% (GSS, 2014a, 2014b). The educational level of respondents from the survey in RVB who are not literate or educated is more than twice the percentage in the Vea community. The educational status of respondents is similar across communities in BVB.

4.3.2 Household information of respondents

4.3.2.1 Household size

The average household size in RVB is higher than that of BVB. The average household size in RVB is nine members per house compared to an average of seven household members in BVB. The results from the survey further showed that there are more respondents in RVB with a household size of 11 members than in BVB with more house sizes of ≤ 5 members. The 2021 population census data collaborate with this survey data by showing that the average size of households in RVB is more than that of BVB by almost 2 members (GSS, 2021). The possible reasons for the larger household size in RVB than in BVB could be the higher general fertility rate and in-migration. The general fertility rate in RVB is 101 births per 1000 women compared to that of BVB, which is 81 births per 1000 women (GSS, 2014b, 2014a). Also, the recorded in-migration in RVB is about 10% more than that of BVB, increasing the number of people in the households as migrants, especially male migrants, who prefer to marry native women to access croplands (GSS, 2014b, 2014a).

4.3.2.1 Household status or position

The survey focus was to target household heads in the study sites. However, in the absence of a household head, the immediate household member available is interviewed. The results showed that 55% of the respondents surveyed in RVB were household heads, while 45% were household members. In BVB, 64% of the respondents surveyed were household heads, while 36% were members. Furthermore, about 20% of the household head surveyed were female compared to about 80% of males in RVB and BVB. As noted earlier, traditional certain in Northern Ghana allow women to be household heads in the absence of a husband in the case of death or permanent migration elsewhere. In this study, the female household heads were purposefully selected, and those who were household members were interviewed in the absence of the household head.

4.3.3 Other background information

4.3.3.1 Primary occupation

The occupations available to farmers in RVB and BVB include farming, service provision and manufacturing/industry. However, as noted earlier, the principal activity for residents in both study sites is farming. In RVB, 93% of the respondents surveyed have farming as the primary occupation, while only 7% have service or manufacturing as the primary source. The percentage in BVB is even higher, as 96% of respondents have agriculture as their primary livelihood activity, and only 4% engage in services or manufacturing. Records show that about 72% of the adult population in RVB and 78% in BVB are into agriculture, while the rest are into services and industry (GSS, 2014a, 2014b). The percentage of respondents in the study sites is higher than the census data because the study sites were all in rural areas where agriculture is very active than other types of occupations. Some respondents also have secondary occupations as alternative livelihood options to supplement food security and financial needs.

4.3.3.2 Years of farming

The survey shows that respondents in RVB have longer farming experience than respondents from BVB. From the survey, 73% of respondents in RVB have over 16 years of farming experience, compared to the 53% in BVB with the same years of farming experience. Of the respondents whose farming experience is five years and below, 23% are from BVB, while only 7% were found in RVB. As expected, farming experience in RVB and BVB strongly correlates ($p < 0.001$) with the age of respondents. Older farmers are more likely to have longer farming experience than younger farmers with shorter farming experiences. The Vea community has more younger respondents and shorter farming experience because of the opportunities the Vea irrigation dam has opened up for younger farmers to engage in dry season agriculture, instead of migrating for other livelihood opportunities.

4.4 Validation of indicators for SI

This section presents the outcome of the participatory workshops with local stakeholders that validated the biophysical and socioeconomic indicators for SI of crop systems selected from existing literature. This set of indicators enabled the researcher to focus on the relevant factors that may influence SI principles, including productivity, resilience, efficiency and equity within the agroecological system in RVB and BVB.

4.4.1 Biophysical indicators for SI

The biophysical indicators for SI include all the factors related to biophysical or environmental properties that enable SI implementation within the semi-arid agriculture systems in RVB and BVB. Broadly, these factors include farmers' assessment of biophysical properties such as water, soil, ecosystem and crop health-related risks and the on-farm management strategies and technologies implemented to increase the resilience and efficiency of these properties.

From **Table 19** below, the biophysical indicators were first selected from the literature and approved **(√)** or disapproved **(×)** by stakeholders through participatory workshops in RVB and BVB. About 70% of RVB indicators were approved by stakeholders, compared to the 74% approved in BVB. Local stakeholders consider approved indicators as factors that can enable or hinder the implementation of SI principles. The disapproved indicators do not necessarily mean those factors are not relevant but suggest they are often not considered by farmers as relevant or may be unavailable within the agriculture system.

Table 19: *Shows the biophysical risks and on-farm strategies indicators selected by stakeholders in RVB and BVB.*

Category	*Risk/challenges*	*Basin*		*On-farm strategies*	*Basin*	
	Indicators	**RV**	**BV**	**Indicators**	**RV**	**BV**
Water	Erratic rainfall	√	√	Irrigation	√	√
	Change in planting dates	√	√	Mulching	√	√
	Increased temperature	√	√	Water harvesting	√	√
	Limited surface water	√	√	Improved seeds	√	√
	Scarce groundwater	×	×	Cover crops	×	×
	Drought	×	×	Water withdrawals	×	×
	Dry spells	√	√			
	Water pollution	×	×			
Soil	Soil moisture	√	√	Crop rotation	√	√
	Organic matter content	√	√	Erosion control	√	√
	Depleted soil nutrients	√	√	Organic matter	√	√
	Soil erosion	√	√	Chemical fertilisers	√	√
	Soil stress	×	×	Compost	√	√
	Soil type	√	√	Leguminous crops	√	√
Ecosystem	Cutting trees for charcoal	√	√	Reforestation	×	×
	Bushfires	×	√	Conservation agriculture	×	×
	Deforestation	√	√	By-laws	√	√
	Waste disposal	×	×	Natural regeneration	√	√
Crop	Pest invasion	√	√	Seed testing	×	√
	Disease infestation	√	√	Sowing in rows	√	√
	Weed control	×	×	Mixed cropping		
				Pesticides	√	√
				weedicides	×	×

Approved indicator (√); Disapproved indicator (×)

4.4.2 Socioeconomic indicators for SI

The socioeconomic indicators for SI include all the factors related to social and economic properties that enable SI implementation within the semi-arid agriculture systems in RVB and BVB. Broadly, these factors include smallholder farmers' assessment of socioeconomic outcomes (such as crop type, farmland, crop productivity, and incomes) and socioeconomic inputs/outputs (such as alternative livelihoods, migration, FBO, inputs, and services) to increase the resilience and efficiency of these properties.

From **Table 20** below, the socioeconomic indicators were first selected from the literature and approved **(**√**)** or disapproved **(×)** by stakeholders through participatory workshops in RVB and BVB. About 85% of socioeconomic indicators were approved in RVB and BVB by stakeholders., The 15% of indicators disapproved indicators do not necessarily mean those factors are unimportant but suggest they are often not prioritised for increasing yields or building resilience in RVB and BVB.

Table 20: *Shows the socioeconomic outcomes, outputs and input indicators selected by stakeholders in RVB and BVB.*

Agriculture Outcomes	**Basin**		**Agriculture inputs/outputs**	**Basin**	
Indicators	**RVB**	**BVB**	**Indicators**	**RVB**	**BVB**
Crop type			***Assets***		
Primary crop	√	√	TV	×	×
Secondary crop	√	√	Radio	√	√
Land tenure			Internet	√	√
Access to cropland	√	√	Mobile phone	√	√
Cropland ownership	√	√	***Access to Inputs***		
Productivity			Fertilisers	√	√
Estimated yields	√	√	Improved seeds	√	√
Actual yields	√	√	Agrochemicals	√	√
Consumed yields	√	√	Farm tools	√	√
Sold yields	√	√	***Access to services***		
Other uses	√	√	Extension	√	√
Economic			Information	√	√
Incomes from yields	√	√	Machinery (tractor)	√	√
Incomes alternative options	√	√	Storage	×	×
Remittances	√	√	Market	√	√
Savings	√	√	***Off-farm activities***		
Loans	√	√	Alternative livelihood option	√	√
Credit	√	√	Migration	√	√
Insurance	×	×	***Other social factors***		
expenditure	√	√	Conflicts over resources	×	×
Food security			Gender inclusion	√	√
Food availability	√	√	Labour	√	√
Food access	×	×	Road network	√	√
Food utilisation	×	×	Village Savings and Loans Association (VSLA)	√	√

Approved indicator (√); Disapproved indicator (×)

4.5 Key Insights

The characteristics of the study area were mostly similar, while a few others differed. The location of the RVB and BVB along the same latitude suggests that most of the physical characteristics, such as rainfall, soils, relief, vegetation and geology and its related socioeconomic characteristics (including livelihood activities) and institutional structures are similar. However, the study sites differed in other characteristics, such as population density, major drainage systems, infrastructure, education status, ethnicity and languages. These characteristics show that although semi-arid areas in Northern Ghana may have some similar features, especially physical characteristics, there is more socioeconomic diversity between locations. These characteristics helped to contextualise the broader study area where specific communities were purposefully selected for the survey.

Furthermore, the results of the demographic characteristics from the survey show that the percentages for the randomly sampled respondents and their households were similar between basins for gender, marital status, household status and primary occupation. However, there were large households with more educated members who were older with more farming experiences in RVB than in BVB. These similarities and differences between the study sites were useful for establishing associations among indicators within and between basins.

Moreover, more than two-thirds of the biophysical and socioeconomic indicators selected from the literature review were approved by stakeholders as critical indicators relevant for analysing the crop production system in RVB and BVB. The few indicators that were not approved were considered duplicate indicators, unmeasurable, or relevant for sustainable crop production in case study sites.

4.6 Summary

The chapter described the characteristics of the study area, the background of respondents and the indicator validation by stakeholders in RVB and BVB. The study area described the site location with a map, the physical features, socioeconomic characteristics and administrative/institutional structures in RVB and BVB. Respondents' demographic characteristics included individual background information, household characteristics and other background information, including years of farming and primary occupation. Respondents' background information is relevant to understanding the dynamics within the factors that influence sustainable intensification in RVB and BVB. Local stakeholders approved the majority of the SI indicators selected from the literature. The next chapters examine and compare the biophysical, socioeconomic and institutional characteristics/indicators that can enable or hinder smallholder farmers from achieving SI goals in RVB and BVB.

CHAPTER 5

BIOPHYSICAL CHARACTERISTICS OF CROP PRODUCTION SYSTEMS IN RVB AND BVB WITHIN SEMI-ARID NORTHERN GHANA, AND IMPLICATION FOR SI

5.1 Introduction

This PhD aims to determine the factors contributing to productivity differences between RVB and BVB and how these factors could influence the implementation of SI within smallholder crop production systems in semi-arid Northern Ghana. The study's objectives are to assess and compare the biophysical, socioeconomic and institutional characteristics of the crop production systems that could hinder or enable SI in Northern Ghana. The chapter in objective 1 examines and compares the biophysical characteristics of the crop production system in RVB and BVB and discusses their implications for implementing SI in semi-arid Northern Ghana. The chapter answers these broader questions: *i)* What are the biophysical characteristics (risks and responses) of semi-arid Northern Ghana that can hinder or enable crop production in RVB and BVB? and *ii)* What implications will biophysical risks and responses have on achieving SI goals of productivity, resilience, efficiency and equity in RVB and BVB? Two types of data are used: primary data from household surveys, KIIs and FGDs, and secondary data from various sources that quantify some characteristics, including rainfall, soils, and crop health.

The chapter covers the following sections: **5.2** presents results of farmers' biophysical factors (risk perceptions and adopted on-farm strategies) alongside available secondary data on these factors between basins; **5.3** analyses the associations between biophysical factors and other survey information (yield, demographic and socioeconomic data) within and between basins; **5.4** discusses the findings alongside previous studies in Northern Ghana and their implications for SI principles (productivity, resilience, efficiency and equity); **5.5** looks at the practical application of SI in Northern Ghana and West Africa based on the findings; **5.6** summaries the chapter.

5.2 Results: Biophysical risk perception and on-farm response strategies

5.2.1 Biophysical risk perceptions

The biophysical risks assessed include; those that are water-related (erratic rainfall, change in planting dates, increased temperature, scarce water for irrigation), soil-related (soil moisture, poor organic matter, depleted soil nutrients, and soil erosion), ecosystem-related (tree cutting for charcoal/firewood, reduction of tree cover and occurrence of bushfires) and crop health-related (occurrence of pest and disease). Respondents ranked their perceived risks on a Likert scale of 1 to 5 (1 = Very low, 2 = low, 3 = Medium, 4 = High, and 5 = Very High). To simplify the description and explanation of the results, 1 and 2 are combined into a single "Minimum risk" category, 3 is assigned to "Moderate risk", and 4 and 5 to "Maximum risk". Percentage stacked bar charts show respondents' biophysical risk perceptions in the RVB and BVB based on their recollection of the past 10 years (2011 - 2020). Pearson's t-test assesses whether the differences are statistically significant between basins for the average/composite biophysical water, soil, ecosystem and crop health-related risks. Chi-square tests also assess whether the differences between basins for individual biophysical risk perceptions are statistically significant.

5.2.1.1 Water-related risks perception

Figure 7 below shows respondents' water-related risk perceptions to crop productivity, including erratic rainfall, change in planting dates, increased temperature, scarce water for irrigation, and severe floods between RVB and BVB. Respondents in RVB are more likely than those in BVB to perceive erratic rainfall, increased temperatures, dry spells and changing planting dates as maximum risks to crop production. However, respondents in BVB are more likely to perceive changing planting dates as a moderate risk than those in RVB. Perceptions of water scarcity for irrigation are the same in RVB and BVB, as about 60% perceive it as a maximum risk. Flood

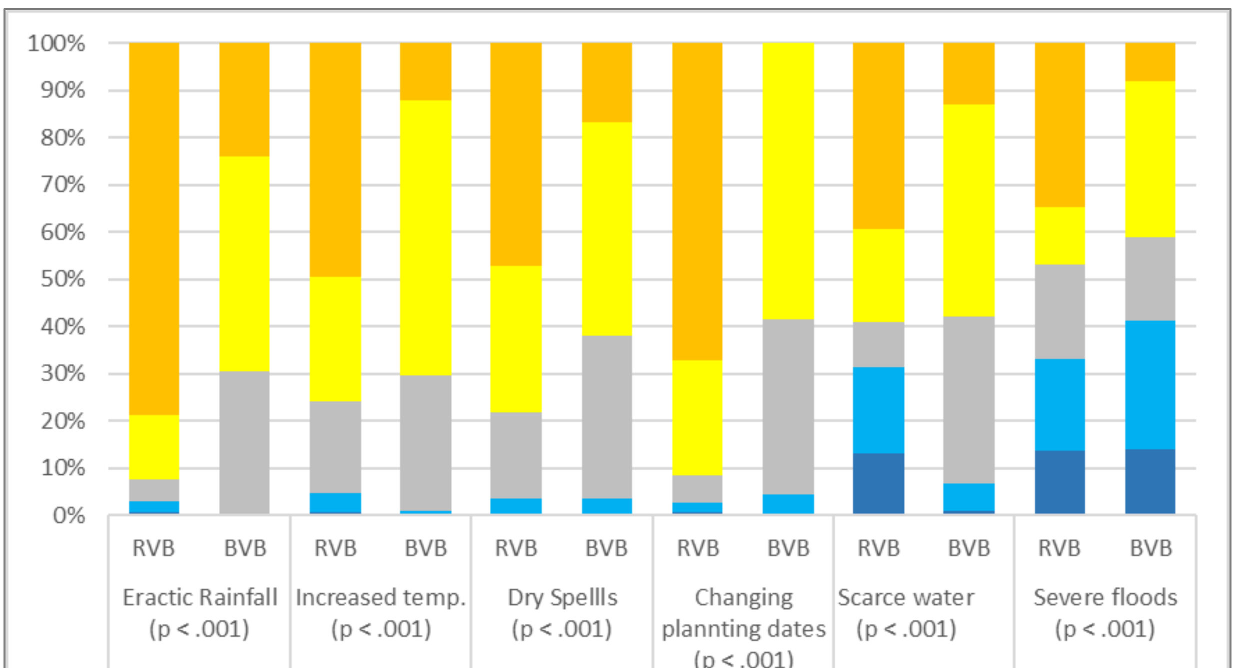

***Figure 7**:100% stacked bar chart and Chi-square results comparing respondents' perception of observed climate/water-related risks in RVB and BVB.*

occurrence is perceived as a minimum to moderate risk by more than half of respondents in RVB (about 53%) and BVB (58%).

The Pearson's t-test result ($p < 0.001$) for the average composite Likert scale score shows that respondents in RVB (4.05) are more likely to have a negative (maximum risk) perception of water-related risks than those in BVB (3.5). However, a decade of rainfall data (2009 – 2020) shows that respondents in BVB than RVB may be at risk of rainfed farming if the recorded trends in the last two years (2019-2020) continue. As shown in **Table 21** below, comparing the annual averages for the first half (2009-2014) to the second half (2015-2020) of the decade shows increases in rainfall amount in RVB (+51%) over BVB (+4%), decreased rainy days in BVB (-13%) over increases in RVB (+59%) and an increased intensity in BVB (+19%) over reduction in RVB (-7.4%).

Erratic rainfall affects rainfall amount, frequency, and intensity, exacerbating the incidence of dry spells, water scarcity, droughts, planting dates, and floods (I. Niang et al., 2015). Respondents' perceptions of erratic rainfall may be due to experiences around one or more of these characteristics, especially for increased rainfall amount and rainy days in RVB and reduced rainy days and increased intensity in BVB.

Table 21: *Rainfall amount, number of rainy days, and rainfall intensity from 2009 to 2020 for RVB and BVB (12 years was picked to match the range of years the perception question was asked).*

Year	Annual rainfall (mm)		Number of rainy days		Rainfall intensity (mm)	
	RVB	*BVB*	*RVB*	*BVB*	*RVB*	*BVB*
2009	1,032	1066	52	79	19.8	13.5
2010	573	1005	45	68	12.7	14.8
2011	727	1022	47	61	15.5	16.8
2012	870	948	41	65	21.2	14.6
2013	991	990	46	63	21.5	15.7
2014	860	937	32	61	26.9	15.4
2015	910	720	67	59	13.6	12.2
2016	838	775	52	56	16.1	13.8
2017	997	1078	72	54	13.8	20.0
2018	1,388	1372	84	65	16.5	21.1
2019	1,624	1195	65	58	25.0	20.6
2020	1,883	1083	79	54	23.8	20.1

Source: (DOA-Bongo, 2020; DOA-Lawra, 2020). *The data received from the DoA is from the averages of three local weather stations in the RVB and two local weather stations in the BVB.*

5.2.1.2 Soil-related risks perception

Figure 8 below shows respondents' soil-related risks perception to crop productivity, including reduced soil moisture, poor organic matter, depleted soil nutrients, and soil erosion between RVB and BVB. Respondents in RVB are more likely than those in BVB to perceive depleted soil nutrients, poor organic matter content and limited soil moisture as maximum risks to crop production. However, erosion occurrence remains a minimum to moderate risk to more respondents in RVB (55%) and BVB (60%), while less than half consider it a maximum risk.

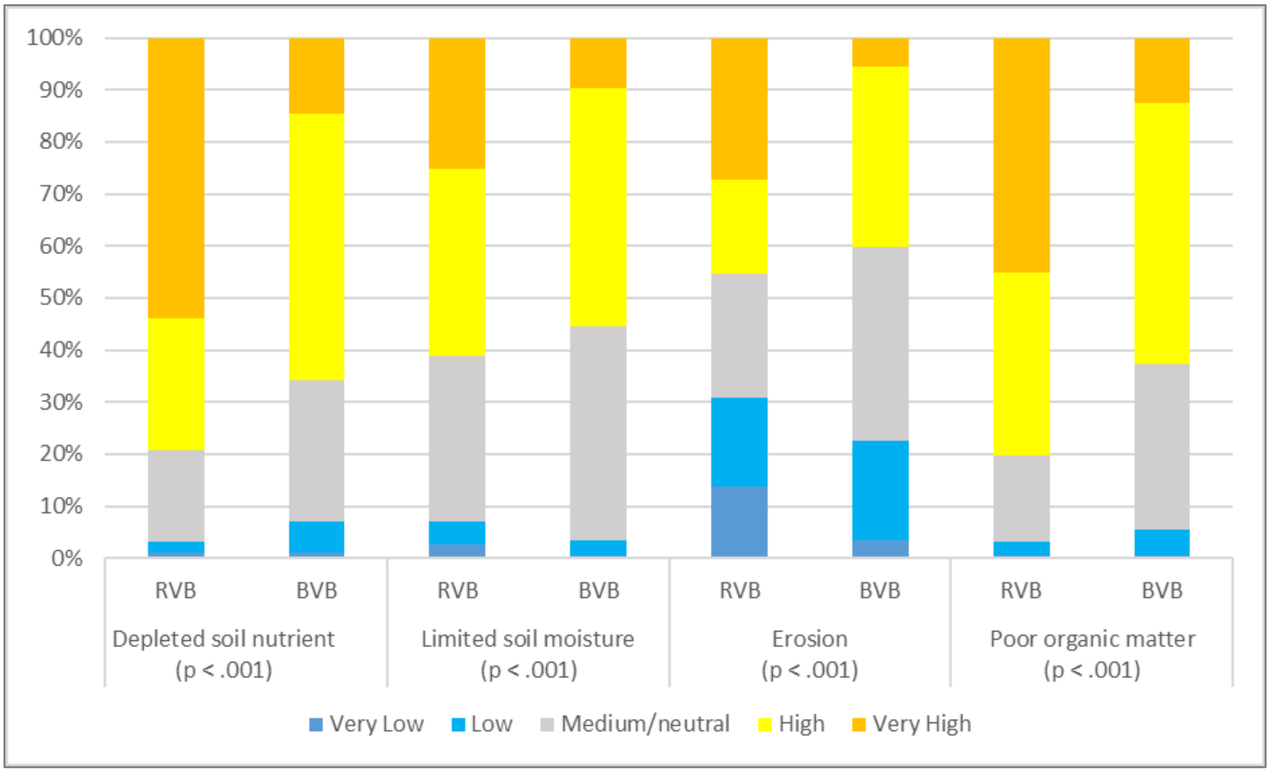

***Figure 8:** 100% stacked bar chart and Chi-square results comparing respondents' perception of observed soil-related risk between RVB and BVB.*

The Pearson's t-test result ($p < 0.002$) for the average composite Likert scale score shows that respondents in RVB (3.8) are more likely to have a negative (maximum risk) perception of soil-related risks than those in BVB (3.3). In **Table 22** below, soil sample data from RVB and BVB suggest that except for soil pH and Total Nitrogen (N), the other soil components, including organic matter content and available Brays (Phosphorous (P) and Potassium (K)), are unsuitable/low for crop production, especially cereals. Soil pH of 5.88 to 6.0 (5.6-7.8 optimum) and Total Nitrogen (N) of 3.0g/kg (≥ 0.3%) (above 1.0g/kg (> 0.1%) optimum) is suitable for cereal production in both basins. Soil organic matter content is higher in BVB (9.7%) than RVB

(5.6%), even though they are not suitable (below meaningful levels of ≥ 15%) for crop production. Available Brays (P and K) in both basins are lower than required (P ≥ 10ppm and K requires 78–117ppm) for crop production.

Furthermore, both basins' low soil water holding capacity is due to low clay and high sand percentages, even though there are more clay particles in BVB than in RVB. As seen in **Table 22,** RVB has about 68% sand and 3% clay particles making it more susceptible to erosion, moisture loss and nutrient leaching than the BVB, with about 59% sand and 8% clay.

Table 22: *Comparing soil sample range and mean (pH, Total N, Organic matter, depth, P, K, Sand, Soil, silt, and Clay) and texture between RVB and BVB.*

Category	Soil Composition	Unit	RVB			BVB		
			Range	Mean	Status	Range	Mean	Status
General component	pH	(in water)	5.5 – 7.1	6.0	*Suitable*	5.5 – 6.36	*5.84*	*Suitable*
	Total Nitrogen	%	0.2 – 0.5	0.3	*Moderate*	0 - 1	*0.33*	*Moderate*
	Organic matter	%	3.4 – 10.7	5.6	*Unsuitable*	0 – 19.3	*9.7*	*Unsuitable/marginal*
	Depth	Cm	*0 – 40*	-	*Marginal*	0 – 40	-	*Marginal*
Bray's available	Phosphorus (P)	ppm	1.75 – 14.9	6.3	*Unsuitable*	0.72 – 16.4	*3.7*	*Unsuitable*
	Potassium (K)	ppm	19.6 - 46	32.4	*Unsuitable*	45 – 129.5	*57.13*	*Marginal*
Particles size analysis	Sand	%	38.6 – 80.4	67.6	*Unsuitable*	31.7 – 75.2	*59.46*	*Marginal/unsuitable*
	Silt	%	11.0 – 65.7	28.4	*Moderate*	22.4 - 44.3	*32.52*	*Moderate*
	Clay	%	1 - 17	3.1	*Suitable*	2 – 24.16	*8.03*	*Suitable*
	Texture		Sandy Loam		*Moderate*	*Sandy Loam*		*Moderate*

Source: (Tetteh et al., 2016). *This data was part of an extensive soil sample analysis obtained from 71 sites in Northern Ghana through the Africa Rising Project. Seven soil samples from seven communities/sites, including the study communities in the Red Volta basin. Five soil samples were collected from the five communities/sites in the Black Volta basin, including the study communities.*

The soil data suggest that some nutrient components (available K, total N and organic matter content) and clay particles are higher in BVB than RVB, supporting farmers' perception of soil-related risk in both basins. More farmers in the RVB perceive soil-related risks as a maximum risk than in the BVB. The possible reason could be the more extended fallows in BVB than RVB due to lower population density (Tetteh et al., 2016). However, since no field experiments were carried out in the present study, it is difficult to determine whether the marginal differences between the RVB and BVB for soil properties are significant explanatory drivers for crop yield differences.

5.2.1.3 Ecosystem-related risks perception

Figure 9 below shows respondents' ecosystem-related risk perceptions to crop productivity, including deforestation, tree cutting for charcoal/firewood, and bushfires between RVB and BVB. Respondents in BVB (about 72%) are more likely than those in RVB (about 51%) to perceive deforestation as a minimum to moderate risk, while those in RVB (49%) perceive it as a maximum risk than those in BVB (28%). Due to high population density, deforestation in RVB is primarily due to the expansion of farmlands into forest/shrub-covered areas. About 72% of respondents in RVB and BVB perceive charcoal/firewood production as a minimum to moderate risk. Respondents in RVB (60%) are more likely than those in BVB (30%) to perceive bushfires as a minimum risk, while those in BVB (51%) perceive it as a maximum risk than those in RVB (30%).

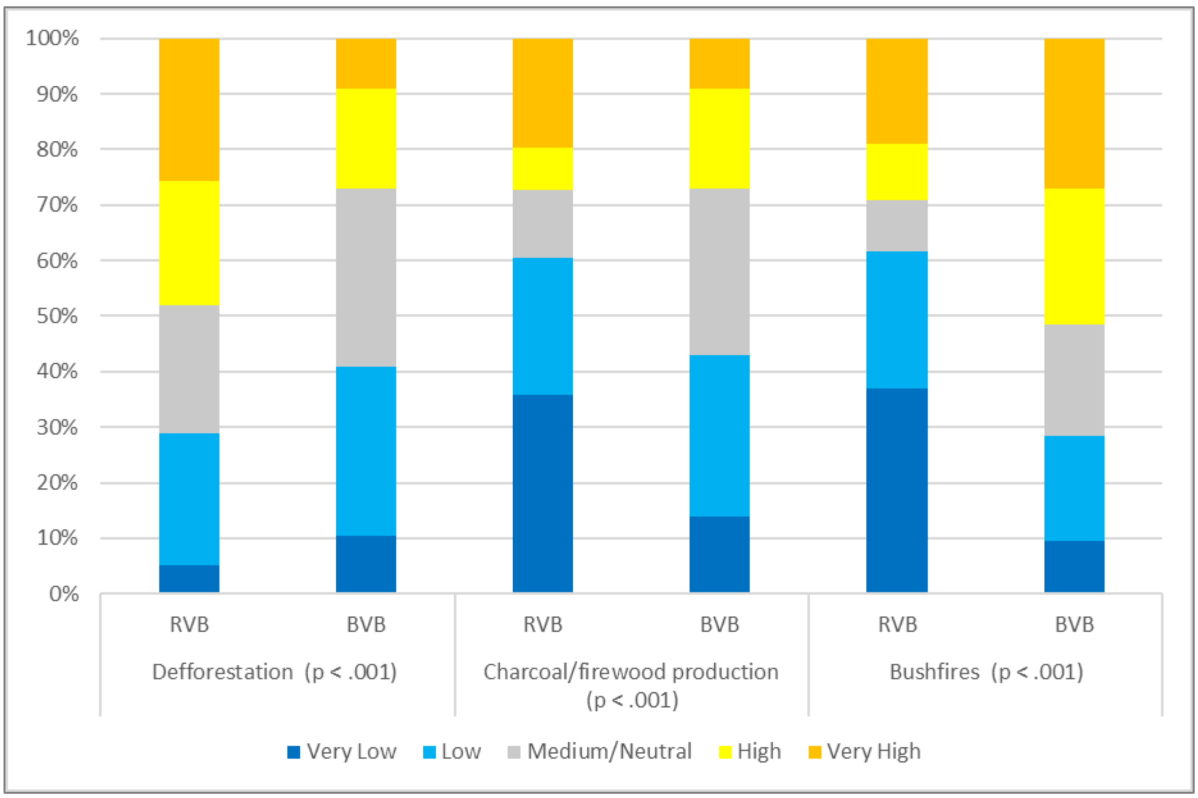

***Figure 9**: 100% stacked bar chart and Chi-square results comparing respondents' perception of observed ecosystem reduction between RVB and BVB*

The Pearson's t-test result ($p < 0.04$) for the average composite Likert scale score shows that respondents in RVB (2.4) are more likely to have a positive (minimum risk) perception of ecosystem-related risks than those in BVB (3.0). Strong by-laws instituted in both basins against ecosystem overexploitation for charcoal, hunting and timber/firewood and increased ecosystem management sensitisation campaigns may explain minimum to moderate risk. A community leader in RVB explained that offenders of overexploitation are reprimanded with community fines or criminal prosecution by the Forestry Commission. According to Boafo et al. (2016), the strength of community enforcement will determine whether the regulations protect the ecosystem's function or lead to compliance.

5.2.1.4 Crop health-related risks perception

Figure 10 below represents respondents' crop health-related risks perception, namely pest and disease infestation in RVB and BVB for the past few years. More respondents in RVB (54%) and BVB (58%) perceive pest infestation as a maximum risk to crop production. Similarly, more respondents in RVB and BVB (about 52%) perceive disease infestation as a moderate to minimum risk to crop production. However, 11% and 18% more respondents in RVB than BVB are likely to perceive pest and disease infestation as a moderate risk. In comparison, 7% and 20% more respondents in BVB than in RVB are likely to perceive pest and disease infestation as a minimum risk.

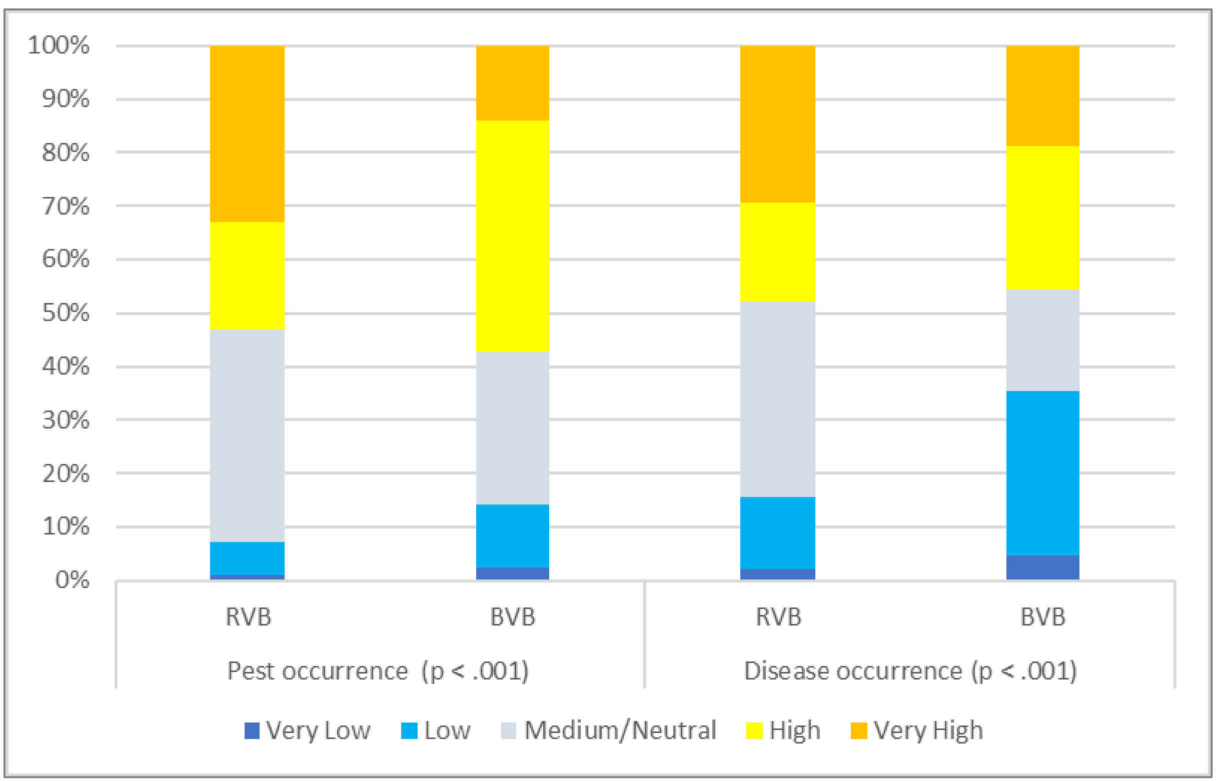

Figure 10: *100% Stacked bar chart and Chi-square results comparing respondents' perception of pest and disease occurrence between RVB and BVB*

A DOA report (2019-2020) supports the perception that pest infestation is a maximum risk in both basins. Records show that pest infestation is higher in RVB than in BVB, especially for the Fall Armyworm (FAW), which is the predominant pest in the region, even though other pests, including aphids, thrips and "stem and fruit" borers, exist. The DOA has taken steps to address FAW infestation in both basins. **Table 23** below shows the hectares of farmland damaged by the FAW; the total area sprayed and recovered in 2019 and 2020.

Table 23: *Farmland affected, sprayed, and recovered from the FAW infestation in 2020 between RVB and BVB.*

Basin	**Total cropland Area (Ha)**	**Total cropland affected (Ha)**	**Total cropland Area Sprayed (Ha)**	**Total Cropland Area Recovered from FAW (Ha)**
Bongo/RVB	13,366	1009 *(7.74%)*	1009 *(7.74%)*	1009 *(7.74%)*
Lawra/BVB	10,413	552.1 *(5.3%)*	552.1 *(5.3%)*	552.1 *(5.3%)*

Source: (Bongo Municipality DOA, 2020; Lawra Municipality DOA, 2020).

The most common crop diseases in both basins include leaf blight, fruit rot and leaf spot. The Pearson's t-test result ($p < 0.001$) for the average composite Likert scale score shows that respondents in RVB (3.55) are more likely to have a negative (maximum risk) perception of crop health-related risks than those in BVB (3.2). In a focus group discussion, farmers in the RVB highlighted that they struggle to contain FAW, as extension support for pest control is often limited.

In summary, more respondents in RVB than BVB are likely to perceive water, soil and crop health-related risks as a maximum risk to crop production. However, respondents in RVB are more likely to perceive ecosystem-related risks as a minimum risk, while those in BVB perceive them as moderate risks to crop production. Besides ecosystem-related risks, secondary data suggest that water, soil, and pest/disease-related risks are threats to current and future crop production systems without implementing sustainable on-farm strategies. The following sections describe the on-farm strategies adopted by respondents to address biophysical risks in RVB and BVB.

5.2.2 *On-farm strategies to manage biophysical risks*

This section identifies the on-farm strategies adopted to manage biophysical risks, their perceived effectiveness, expert advice support, and the reasons for not adopting at least one strategy in RVB and BVB. The on-farm strategies include water, soil, and crop management. Pearson's t-test assesses whether the differences are statistically significant between basins for the number of adopted on-farm strategies. Chi-square tests also assessed whether the differences between basins for individual adopted on-farm strategies are statistically significant.

5.2.2.1 Adoption of on-farm management strategies

For on-farm water strategies, except for water harvesting ($p > 0.05$), Chi-square results show different patterns of adoption between RVB and BVB: improved/drought-resistant seeds ($p = 0.001$), irrigation ($p < 0.001$) and mulching ($p = 0.013$). Respondents in RVB are more likely to adopt improved seeds and irrigation than those in BVB, while those in BVB are more likely to adopt mulching than those in RVB, as shown in **Figure 11** below.

For soil strategies, Pearson's Chi-square results indicate different patterns of adoption for leguminous crops ($p < 0.001$), organic matter ($p < 0.001$), erosion control ($p < 0.001$), chemical fertiliser ($p = 0.033$) and crop rotation ($p = 0.011$) between RVB and BVB. Respondents in RVB are more likely than those in BVB to adopt leguminous crops, organic matter, and erosion control. However, those who are likely to adopt chemical fertilisers and crop rotations are more in BVB than RVB.

For crop management strategies, except for seed testing ($p = 0.119$) and sowing in rows ($p = 0.879$), chi-square results show different patterns of adoption for mixed cropping ($p < 0.001$) and pest/disease control ($p = 0.009$) between RVB and BVB. Respondents who practice mixed cropping and pest/disease control are likely to be more in RVB than BVB.

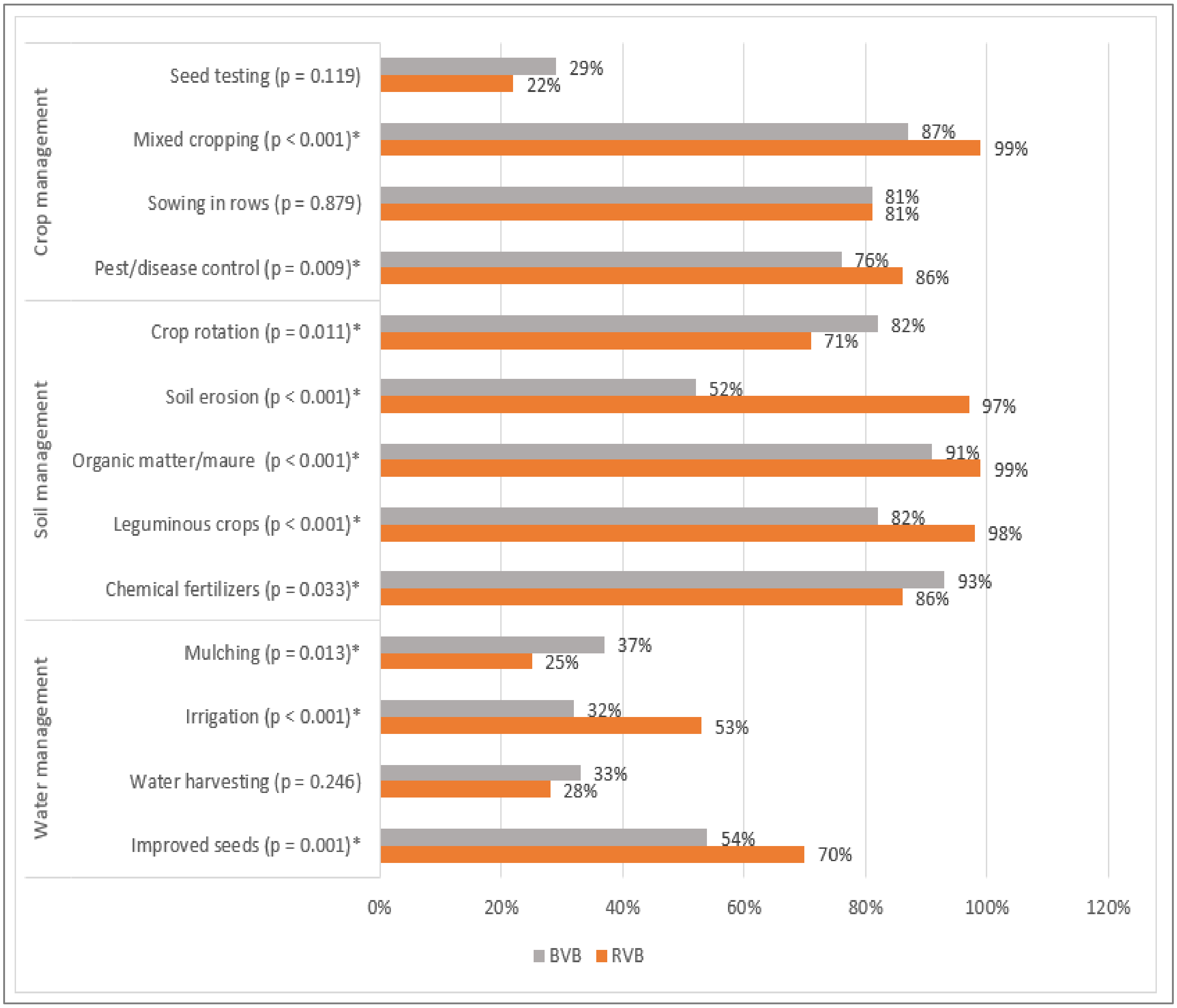

Figure 11: *A percentage bar graph and chi-square results comparing the adoption of on-farm Water, Soil and crop management strategies between RVB and BVB.*

The Pearson's t-test results for the composite number of adopted strategies show that except for crop management ($p > 0.05$), adopted water ($p = 0.021$) and soil ($p < 0.001$) management strategies are differ between RVB and BVB. Respondents in RVB are more likely than those in BVB to adopt on-farm water and soil management strategies in RVB than BVB, while crop management was similar. GIDA report shows that the BVB has fewer irrigation projects (130 small dams and dugouts) than RVB, with about 278 irrigation projects (Namara et al., 2011).

This secondary information, alongside the results that RVB farmers have maximum biophysical risk perceptions, could explain why more respondents in RVB adopted on-farm water and soil strategies than in those in BVB. However, the adoption of water management is relatively low (less than 45%) in RVB and BVB, while soil and crop management strategies are more often adopted (over 70% of respondents). For instance, on-farm water techniques such as water harvesting, mulching and irrigation are low in both basins, especially in BVB, as shown in **Figure 11** above. Similarly, the adoption of crop management strategies like seed testing, which could prevent crop failure, is very low in both basins.

5.2.2.2 Effectiveness of adopted on-farm strategies

This section describes the perceived effectiveness of adopted on-farm strategies in RVB and BVB. A Likert scale of 1 to 5 (where 1 - Very Ineffective, 2 – Ineffective, 3 – Medium, 4 - Effective and 5 - Very Effective) measures the effectiveness of on-farm strategies. To simplify the description and explanation of the results, 1 and 2 are combined into a single "Inefficient strategy" category, 3 is assigned to "Moderate strategy", and 4 and 5 to "Efficient strategy".

Respondents in RVB are more likely than those in BVB to perceive their adopted on-farm water, soil and crop management as efficient strategies. However, those in BVB are more likely to perceive them as inefficient to moderate strategies than those in RVB, as shown in **Figure 12** below. For instance, except for seed testing and irrigation, more respondents in RVB perceived all adopted practices as efficient strategies. Also, besides seed testing, legumes use, irrigation, water harvesting and chemical fertiliser use, more than half of respondents in BVB perceived their adopted on-farm practices as inefficient to moderately efficient strategies.

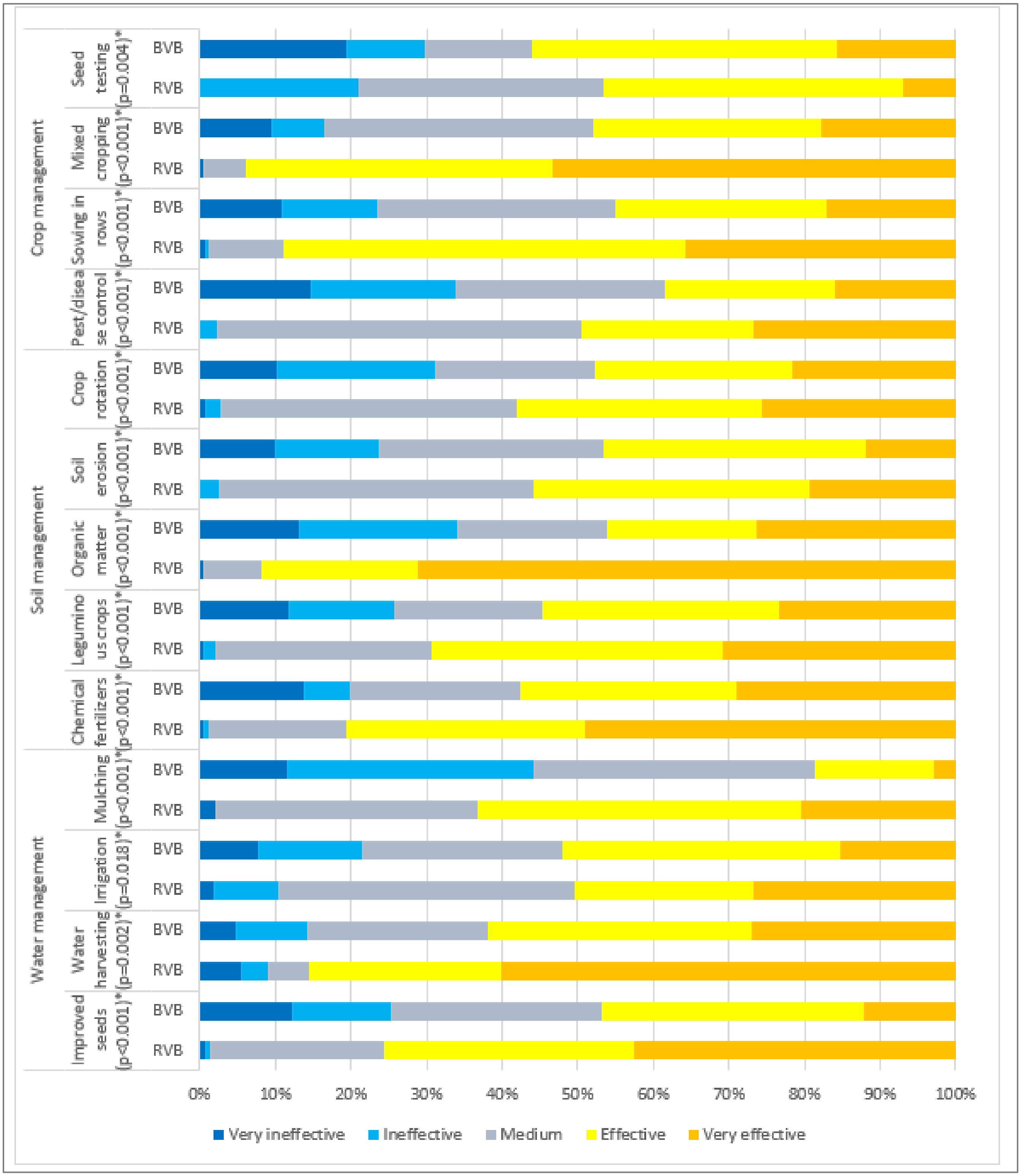

Figure 12: *A 100% bar graph and Chi-square results comparing the effectiveness of water, soil and crop management strategies between RVB and BVB.*

Generally, the composite Likert scale score shows that on-farm water, soil, and crop strategies are 23%, 21% and 31% perceived by farmers to more efficient in RVB than in BVB, while more farmers in BVB consider these strategies to be inefficient (21% for water, 26% for soils and 23% for crop). Also, the composite average perception of adopted on-farm strategy effectiveness differs ($p < 0.001$) between RVB and BVB. The Pearson's t-test and multiple response results show that respondents in RVB (74%) are more likely than those in BVB (49%) to perceive their adopted strategies as efficient. In comparison, those in BVB (51%) are more likely to view them as inefficient to moderate strategies than those in RVB (26%).

5.2.2.3 Extent of expert advice for adopting on-farm strategies

Farmers in RVB and BVB receive agriculture advice from extension officers, input suppliers, experienced farmers, visiting researchers and NGO practitioners. Expert advice through demonstration farms, radio sessions, phone calls, and in-person training. As shown in **Figure 13 below,** respondents in RVB are more likely than those in BVB to receive advice on water strategies, including improved seeds, water harvesting, irrigation and mulching. Besides advice on soil erosion, respondents in RVB are more likely than those in BVB to receive advice on soil management strategies, including chemical fertilisers, leguminous crops, organic matter and crop rotation. Expert advice on crop management strategies, including pest/disease control, sowing in rows, and mixed cropping, is more likely received by respondents in RVB than in BVB. However, seed testing is more likely to be received by respondents in BVB than in RVB.

Pearson's Chi-square results show that except for expert advice on soil erosion, mulching, irrigation and water harvesting, expert advisories on all adopted strategies differed ($p \leq 0.05$) between RVB and BVB, as shown in **Figure 13** below. Generally, Pearson's t-test results show that access to the number of expert advisories differs ($p < 0.001$) between both basins, where respondents in RVB are more likely to have ≥2 agriculture advisories than those in BVB.

DOA data from 2020 shows that a small percentage of farmers in both basins received on-farm management training, even though the number was higher in RVB than in BVB. Out of the 65,936 farmers recorded in RVB, 11% and 4% received advice on soil and crop management, while 7% and 1% received similar advisories on soil and crop management out of the 59,222 farmers in BVB. However, less than 3% in both basins received water management advisories ***(See Appendix F(i))***. As noted earlier, farmers receive expert advice from different sources and not just from the

DOA, explaining why the percentage of expert advice from the survey is higher than from the DOA.

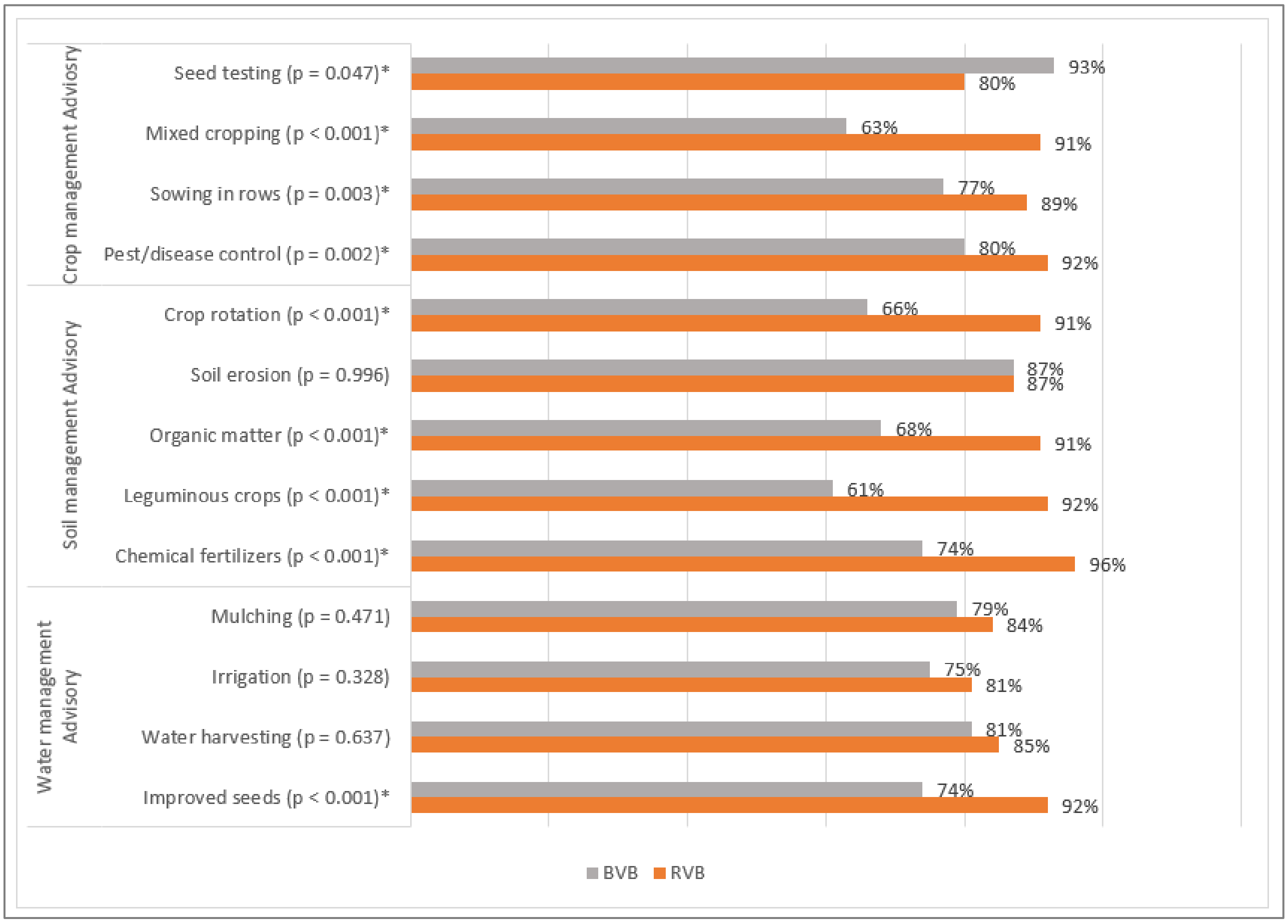

***Figure 13**: A bar graph comparing respondents' percentages and chi-square results who have received expert advice on on-farm strategies between RVB and BVB.*

5.2.2.4 Reasons for the non-adoption of on-farm management strategies

Non-adoption of on-farm management strategies in RVB and BVB are based on cost, unknown strategy (unaware of strategy), insufficient information (no advice on strategy), uncertain outcome (stopped practice strategy due to ineffectiveness) and inadequacy/not enough (inability to practice the strategy).

Figure 14 below shows that more respondents in RVB and BVB did not adopt water management compared to soil and crop management strategies. However, seed testing was the highest non-adopted crop management strategy in both basins. However, crop rotation in RVB and soil erosion strategies in BVB were the highest non-adopted soil management strategies. In RVB, the reasons for the non-adoption of water management strategies are cost-related; soil management strategies are inadequacy of strategy; crop health management strategies are unknown strategies. On the contrary, the reasons for non-adoption in BVB for water, soil and crop management strategies are due to strategies unknown to respondents.

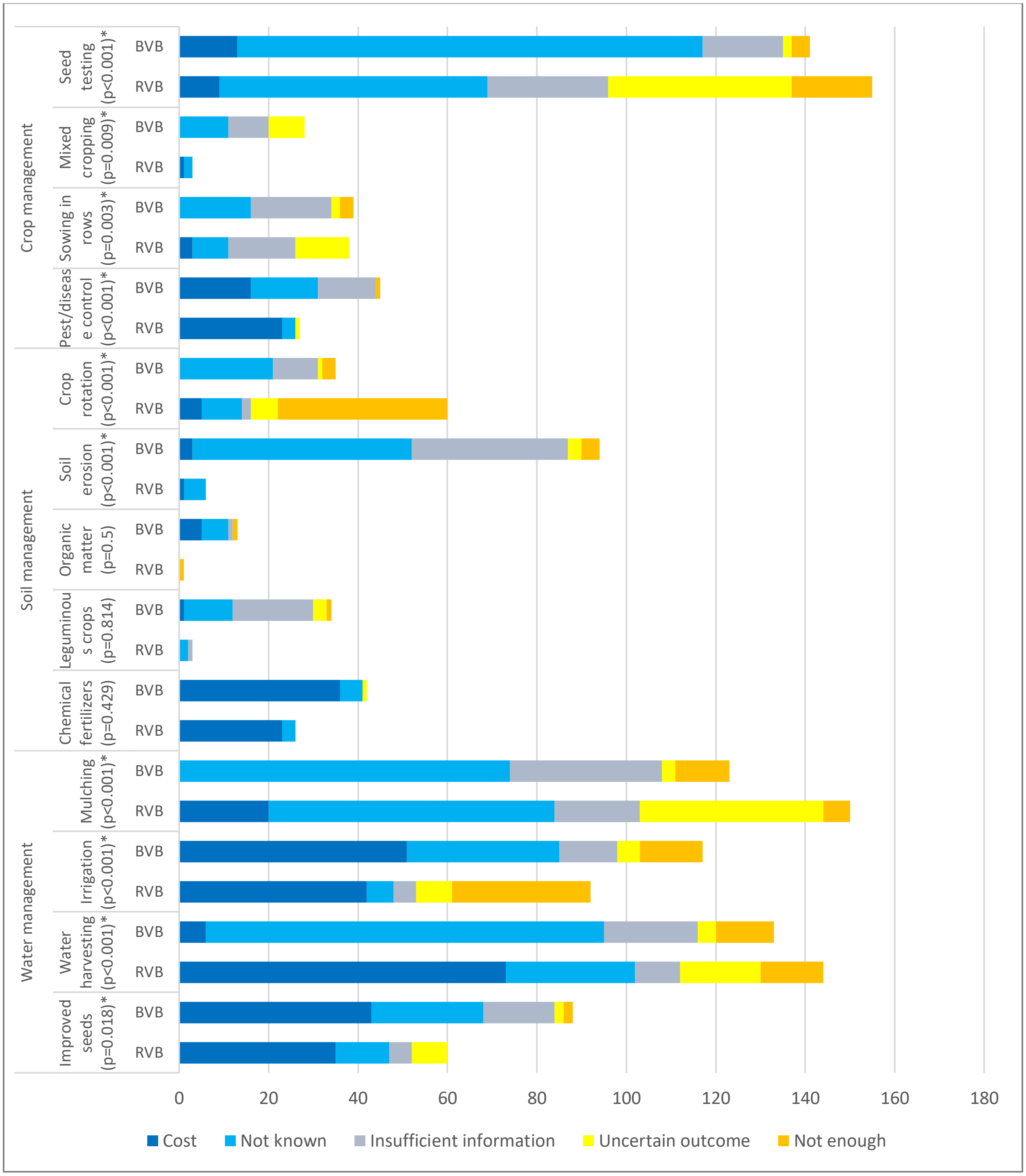

***Figure 14**: A bar graph and Chi-square results comparing the reasons for not adopting on-farm management strategies between RVB and BVB.*

Generally, the top three reasons for non-adoption of on-farm strategies included cost (31%), unknown strategies (27%) and uncertain outcome (18%) in RVB, while BVB included unknown strategies (49%), insufficient information (22%) and cost (19%). Inadequate financial and technical know-how (capacity) dictate non-adoption in RVB, while technical know-how (capacity) and insufficient information/knowledge drive non-adoption in BVB. These results could be useful in promoting agriculture technology or innovation in both basins, as the fundamental reason for non-adoption could be targeted.

Overall, the results showed that respondents in RVB are more likely than those in BVB to perceive biophysical risks as maximum risk, adopt more on-farm strategies, receive more farm advice and consider their adopted strategies as efficient. However, the non-adoption of strategies in RVB is cost and capacity related, while in BVB, they are more related to insufficient information and low capacity. The following section analyses the factors influencing biophysical risk perceptions, adoption of on-farm strategies, access to agriculture advice and strategies' effectiveness.

5.3 Analysis: Determinants of biophysical risks perception and the adoption of on-farm management strategies

5.3.1 Determinants of biophysical risks perception

This section analyses biophysical risk perceptions as determinants of crop productivity and how respondents' demographic and socioeconomic characteristics could influence these perceptions.

5.3.1.1 Biophysical risk perceptions and crop productivity

Spearman's correlations tests show that as respondents' overall average risk perceptions increase, they tend to have lower expected ($r = -0.36$, $p < 0.001$) and actual/produced ($r = -0.38$, $p < 0.001$) yield/ha in RVB. However, no associations were found between the overall average risk perceptions and yields/ha expected ($r = 0.008$, $p = 0.9$) or produced ($r = -0.007$, $p = 0.9$) in BVB. See **Figure 15** below.

Again, MLR test also shows that respondents' actual yield/ha in RVB is more likely to predict their overall average risk perceptions than their expected yield/ha. However, increased biophysical risk perceptions lead to lower actual yield/ha in RVB. No relationships were identified in BVB. See **Table 24** below.

Dummy variables (0,1) are created from Likert scale scores, where 0 is the minimum risk (low, very low, medium) and 1 is the maximum risk (high, very high), and used as independent variables in a stepwise linear regression. The results show that in RVB, respondents with maximum risk perception of increased temperature (R^2 = 0.23), depleted soil nutrients (R^2 = 0.28), severe floods (R^2 = 0.32) and erratic rainfall (R^2 = 0.32) also have lower actual yield/ha. No variable was associated with yield/ha in BVB. See **appendix G** for details.

These results suggest that biophysical risks experienced by respondents could impact crop productivity levels, particularly in RVB.

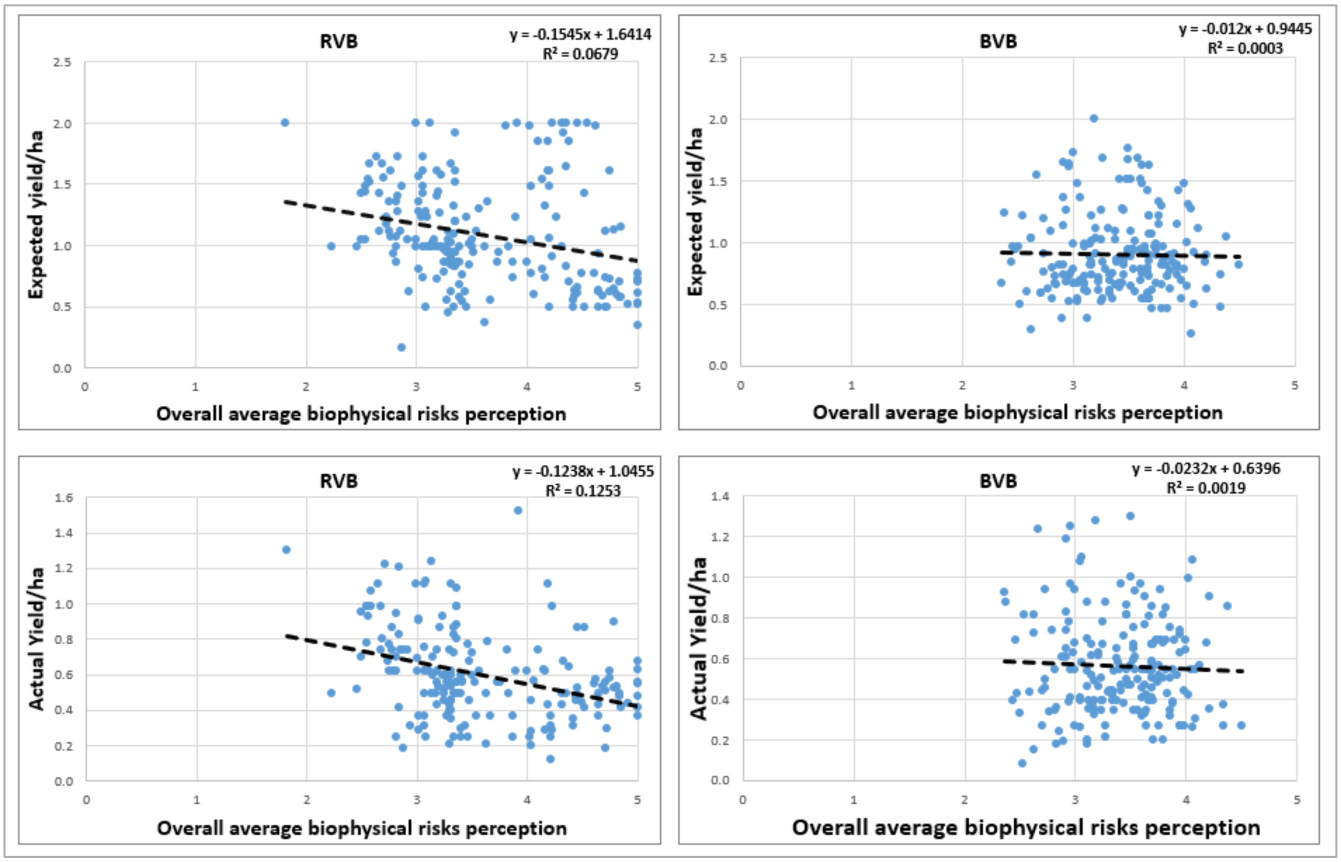

Figure 15: *Scatter plots showing the correlation between crop yield/ha (expected and actual) and overall average biophysical risks perception in RVB and BVB.*

Table 24: *Multiple regression results indicating the beta and p-values of expected and actual yields/ha as determinants of overall biophysical risks perception in RVB and BVB.*

Basin	Yield/ha	β	t	p-value
RVB	*Expected*	-.122	-.949	.344
	Actual	-.853	-3.305	.001*
RVB	*Expected*	.046	.304	.761
	Actual	-.130	-.619	.536

" denotes significance level <= 0.05"*

5.3.1.2 Biophysical risks perception across different communities

In RVB, Pearson's chi-square results indicate different patterns of risk perception ($p \leq 0.05$) for as erratic rainfall, scarce water, dry spells, floods, poor soil nutrients, erosion and limited moisture between respondents from communities with permanent water sources (Vea) and those without (Beo and Lungu), as shown in **Table 25** below. The availability of dry-season irrigation farming along the Vea dam makes respondents from the Vea community less vulnerable to water and soil-related risks than those from Beo and Lungu. However, more farmers from Vea consider poor organic matter content as a maximum risk than those from Beo and Lungu, possibly due to the continued use of irrigated lands leading to soil depletion.

In BVB, the chi-square results show different patterns of risk perception ($p \leq 0.05$) for charcoal/firewood production and scarce water for irrigation between respondents from communities with permanent water sources (Mettow) and those without (Zambo and Yagture). This result could be due to the access to the Black Volta River for dry season farming by respondents in Mettow who perceive scarce water for irrigation as minimum risk. However, those in Zambo and Yagture depend more on ecosystem services to supplement the lack of irrigation opportunities.

Generally, Pearson's t-test shows that except for water-related risk perceptions ($p < 0.001$), respondents' average soil, ecosystem and crop health-related risk perceptions are similar across RVB communities. Similarly, respondents' average water, soil and crop health-related risk perceptions are similar across communities in BVB besides ecosystem-related risk ($p \leq 0.05$). See ***Appendix G (xx)*** for details.

Table 25: *Chi-square results comparing the association (p-values) between communities with and without water sources for biophysical risk perceptions in RVB and BVB.*

Categories/Composite	Biophysical risk perception	P-Values	
		RVB	***BVB***
Water-related risk	Erratic Rainfall	0.002*	0.869
	Increased temp.	0.283	0.537
	Dry Spells	0.05*	0.568
	Changing planting dates	<0.001*	0.449
	Scarce water resources	0.05*	0.02*
	Severe floods	<0.001*	0.578
Soil-related risks	Depleted soil nutrient	0.002*	0.32
	Limited soil moisture	<0.001*	0.355
	Erosion	<0.001*	0.101
	Poor organic matter	0.05*	0.2
Ecosystem-related risks	Deforestation	0.103	0.199
	Charcoal/firewood production	0.906	0.002*
	Bushfires	0.11	0.585
Crop health-related risks	Pest occurrence	0.745	0.316
	Disease occurrence	0.171	0.299

" denotes significance level <= 0.05"*

5.3.1.3 Biophysical risks perception and respondents' gender, age and education

Pearson's chi-square and t-test analysis show that some biophysical risk perceptions differ based on respondents' gender, age category and educational level in RVB and BVB, as shown in **Table 26** and ***Appendix G*** below.

For gender, chi-square results indicate different patterns of risk perception ($p \leq 0.05$) for changing planting dates, scarce water resources, limited soil moisture, poor organic matter content, and pest and disease occurrence between males and females in RVB. Females are more likely to perceive these risks as maximum risks to productivity. In BVB, the results show similar patterns of risk perceptions ($p \leq 0.05$) between males and females, besides crop disease occurrence, where males are more likely than females to perceive as a maximum risk to productivity. T-test results of average biophysical risk categories indicate that females ($p \leq 0.05$) in RVB are more likely than males to perceive water and soil-related risks as maximum risk, while in BVB, males are more likely than females to perceive crop health-related risk as maximum risk. The results in RVB could be due to unequal access to agricultural resources based on gender. Women in RVB explained that they lack inputs (fertilisers, irrigation and seeds) to cope with biophysical risks such as water scarcity, poor soils, and pest infestation. The results in BVB could be due to males being more likely to have access to information delivery devices, including radios ($p = 0.003$), mobile phones ($p = 0.036$) and the internet ($p = 0.05$), which are used as the medium to receive information on crop health-related emergencies like FAW.

For the age category, chi-square results indicate different patterns of risk perception ($p \leq 0.05$) for most biophysical risks between that older (≥40 years) and younger (<40 years) respondents in RVB besides erratic rainfall, changing planting dates and soil erosion. Older respondents are more likely to perceive most risks as maximum risks to productivity. However, in BVB, the results show that older respondents are more likely than younger respondents to perceive limited soil moisture, erosion, poor organic matter content, deforestation and bushfires as maximum risks. T-test results show that the older respondents are more likely to perceive water, soil, ecosystem and crop health-related risks as maximum risks. In BVB, older respondents are more likely to perceive soil and ecosystem-related risks as maximum risks, while water and crop health-related risks remain the same across age groups. A possible reason for these outcomes could be that older respondents have longer experiences coping with biophysical risks and their impacts, viewing them more negatively than younger respondents.

For educational level, chi-square results indicate different patterns of perception ($p \leq 0.05$) for most biophysical risks between educated and less-educated respondents in RVB besides erratic rainfall, changing planting dates and disease occurrence. Less-educated respondents are more likely than educated respondents to perceive these risks as maximum risks to productivity. However, in BVB, the pattern of risk perception is similar for almost all biophysical risks regardless of educational status besides soil erosion, which less-educated respondents are more likely than educated respondents to perceive as a maximum risk. T-test results of biophysical risk categories show that except for ecosystem risks, less-educated respondents are more likely ($p \leq 0.05$) than educated respondents to perceive water, soil and crop health-related risks as maximum risks. However, in BVB, water, soil, ecosystem, and crop health-related risk perceptions are similar ($p > 0.05$) among respondents regardless of educational status. Educated respondents may have access to different sources of information to manage biophysical risks, making them less vulnerable to biophysical risks.

These analyses suggest that respondents' gender, age and educational level could be determinants of biophysical risk perceptions, especially for water, soil and crop health-related risks in RVB.

Respondents in BVB seem to have similar perceptions of soils and ecosystem risk regardless of gender, education and age. Also, erratic rainfall, changing planting dates and depleted soils seem to be the most critical risks, as perceptions are similar across gender, age and education in RVB and BVB.

Table 26: *Chi-square results comparing the associations (p-values) within gender, age and education groups for biophysical risk perceptions in RVB and BVB.*

Categories	Biophysical perception	Pearson's Chi-square P-Values					
		Gender		Age		Education	
		RVB	***BVB***	***RVB***	***BVB***	***RVB***	***BVB***
Water-related risk	Erratic Rainfall	0.408	0.703	0.576	0.34	0.753	0.666
	Increased temp.	0.394	0.633	0.009*	0.137	0.009*	0.725
	Dry Spells	0.457	0.295	0.003*	0.147	0.018*	0.127
	Changing planting dates	0.048*	0.531	0.224	0.718	0.575	0.706
	Scarce water	0.04*	0.567	0.026*	0.242	0.005*	0.16
	Severe floods	0.425	0.428	0.012*	0.233	0.05*	0.295
Soil-related risks	Depleted soil nutrient	0.336	0.743	0.005*	0.41	0.184	0.208
	Limited soil moisture	0.046*	0.428	0.006*	0.005*	0.004*	0.512
	Erosion	0.404	0.831	0.014*	0.012*	0.007*	0.04*
	Poor organic matter	0.03*	0.407	0.844	0.048*	0.013*	0.11
Ecosystem-related risks	Deforestation	0.261	0.395	0.009*	0.002*	0.022*	0.325
	Charcoal/firewood production	0.63	0.116	0.004*	0.268	0.008*	0.802
	Bushfires	0.711	0.911	0.003*	0.011*	0.003*	0.852
Crop health-related risks	Pest occurrence	0.048*	0.507	0.042*	0.379	0.035*	0.252
	Disease occurrence	0.03*	0.017*	0.04*	0.64	0.285	0.605

" denotes significance level <= 0.05"*

5.3.1.4 Biophysical risk perceptions and access to information and extension services

Pearson's chi-square and t-test analysis show that some biophysical risk perceptions differ based on respondents' access to extension services and information in RVB and BVB. See **Table 27** and ***Appendix G*** below.

Chi-square results indicate different patterns of perceptions for most biophysical risks between respondents with access to information and those without in RVB, apart from changing plating dates and pest/disease occurrence. Respondents with access to information are more likely to perceive most risks as maximum risks to productivity. However, respondents without access to information are more likely to perceive water scarcity for irrigation as a maximum risk than those with access to information. In BVB, the chi-square results show different patterns of perception for most biophysical risks besides increased temperature, scarce water resources and pest occurrence. Respondents with access to information are more likely than those without to perceive most risks as maximum risks. T-test results show that water, soil, ecosystem and crop health-related risk categories differ ($p \leq 0.05$) with access to information. Those with information access are more likely to perceive these risks as maximum risks than those without in RVB. However, in BVB, respondents without information access are more likely to perceive soil, ecosystem and crop health categories as maximum risks than those with information. The results in RVB could suggest that farmers who struggle (maximum risk) with water and soil-related risks often seek information to improve water and soil properties. However, in BVB, the results could also mean farmers with access to information can better manage soil and ecosystem-related risks and may perceive them as minimum/moderate risks.

Furthermore, the Chi-square results indicate similar patterns of perception for biophysical risks regardless of extension access. However, the results in BVB show different patterns of perceptions for most biophysical risks, apart from increased temperatures, changing planting dates, scarce water resources, poor organic matter content and charcoal/firewood production. Respondents in BVB without extension service access are more likely than those with access to perceive most risks as maximum risks to productivity. T-test results in RVB show that water, soil, ecosystem and crop health-related categories are perceived as maximum risk regardless of extension services. However, in BVB, soils and ecosystems-related risks categories are perceived as maximum risks among respondents without extension access. However, those with extension services are more likely ($p \leq 0.05$) to perceive crop health-related risks as maximum risks to productivity. The outcome in BVB could mean that extension services enable farmers to cope with soil and ecosystem risks while those without may be affected more. Also, respondents with access to extension services in BVB often seek help to control pests and diseases, especially FAW, perceiving them as maximum risks. However, in RVB, extension services are high among farmers, explaining the similarities in biophysical risk perceptions.

Table 27: *Chi-square results comparing the associations (p-values) between respondents with extension and information access and those without access for biophysical risk perceptions in RVB and BVB.*

Categories	Biophysical perception	Chi-Square P-Values			
		Extension		Information	
		RVB	***BVB***	***RVB***	***BVB***
Water-related risk	Erratic Rainfall	0.126	0.04*	0.037*	<0.001*
	Increased temp.	0.221	0.429	<0.001*	0.477
	Dry Spells	0.922	0.005*	0.001*	0.027*
	Changing planting dates	0.333	0.611	0.192	0.05*
	Scarce water	0.372	0.589	<0.001*	0.229
	Severe floods	0.614	0.002*	<0.001*	<0.001*
Soil-related risks	Depleted soil nutrient	0.133	0.019*	<0.001*	<0.001*
	Limited soil moisture	0.448	0.043*	<0.001*	0.025*
	Erosion	0.705	0.032*	<0.001*	0.026*
	Poor organic matter	0.678	0.369	0.048*	0.010*
Ecosystem-related risks	Deforestation	0.534	0.003*	<0.001*	0.022*
	Charcoal/firewood production	0.801	0.158	0.002*	0.004*
	Bushfires	0.953	0.015*	<0.001*	0.001*
Crop health-related risks	Pest occurrence	0.295	0.004*	0.37	0.104
	Disease occurrence	0.841	0.004*	0.398	<0.001*

" denotes significance level <= 0.05"*

Binary logistic regression analysis showed that information and extension services are more tightly linked in BVB ($p = 0.006$) than in RVB ($p = 0.421$). This outcome could also explain why more respondents without information and extension access negatively perceive soil and ecosystem risks in BVB.

5.3.1.5 Cropland size, access to inputs and services, and expenditure as determinants of biophysical risks perception

It is assumed that respondents' cropland size, access to inputs and services, and farm expenditure are critical resources for farming. MLR test was conducted to identify any association between these variables (independent) and the overall average biophysical risk perceptions (dependent variable). See **Table 28** for details.

In RVB, respondents' cropland size, inputs access, services access, and farm expenditure could predict ($R^2 = 0.25$, $p \leq 0.05$) their biophysical risk perceptions. In BVB, besides expenditure, inputs access, services access and the cropland size were predictors ($R^2 = 0.15$, $p \leq 0.05$) of biophysical risk perception.

Biophysical risk perception increases with cropland size in RVB and BVB. This outcome could be due to more resources required to manage bigger/increased croplands, where the impact of extreme biophysical risks (dry spells, erratic rainfall, and degraded soils) may be more severe than in smaller croplands. Also, in RVB, access to inputs and services increases biophysical risk perceptions. Respondents mostly affected by biophysical risks access inputs and services to manage these risks. However, in BVB, an increased access to inputs and services reduces the adverse biophysical risk perceptions. Unlike RVB, respondents in BVB often access inputs and services through input retailers, who supply timely inputs/services to address biophysical risks. Also, biophysical risk perceptions increase with farm expenditure in RVB, not BVB. This outcome suggests that in RVB, the severity of biophysical risks increases financial investment to manage them.

Table 28: *Multiple linear regression results showing cropland size, number of inputs and services and farm expenditure as determinants of biophysical risks perception in RVB and BVB.*

Basin	Variables	Unstandardized Coefficients	Std. Error	t	p-value
RVB	*Cropland size (ha)*	0.256	0.04	6.425	<.001
	Access to inputs	0.055	0.09	0.607	0.02
	Access to services	0.114	0.028	4.05	<.001
	Expenditure	0.001	0	-7.757	<.001
BVB	*Cropland size (ha)*	0.051	0.032	1.567	0.04
	Access to inputs	-0.283	0.104	-2.738	0.007
	Access to services	-0.356	0.126	-2.824	0.005
	Expenditure	-3.31E-05	0	-0.634	0.527
Dependent Variable: Overall average biophysical perception					

" denotes significance level <= 0.05"*

5.3.2 *Determinants of on-farm strategies adoption*

This section analyses adopted on-farm management strategies and how respondents' yield levels, and demographic and socioeconomic characteristics, including biophysical risk perceptions, could influence their adoption pattern.

5.3.2.1 On-farm management strategies and crop productivity

The Spearman's correlations test shows that respondents in RVB who adopt more on-farm strategies also have lower expected ($r = -0.151$, $p = 0.03$) and actual/produced ($r = -0.115$, $p = 0.05$) crop yield/ha. However, in BVB, no associations were found between the number of on-farm strategies adopted and yields/ha expected (r = 0.026, p = 0.4) or produced (r = -0.002, p = 0.5). See **Figure 16** below.

Furthermore, stepwise linear regression shows that in RVB, the expected yield/ha increases with the adoption of water harvesting ($R^2 = 0.15$) while decreasing with crop rotation ($R^2 = 0.22$) and mulching ($R^2 = 0.24$). However, actual yield/ha produced increases the adoption of pest/disease control and practicing sowing in rows while reducing with adopted crop rotation. In BVB, respondents who use improved seeds could increase their crop yield/ha expectations ($R^2 = 0.11$) and the actual yield/ha produced ($R^2 = 0.08$). However, seed testing ($R^2 = 0.05$) before sowing reduces yield/ha expectations, while mixed cropping ($R^2 = 0.04$) and erosion control ($R^2 = 0.08$) also reduces actual yield/ha produced. See **appendix G** for details.

The possible reason some adopted on-farm strategies may have negative effects on yield outcomes could be the lack of capacity to efficiently practice these strategies, resulting in maladaptation which affects productivity.

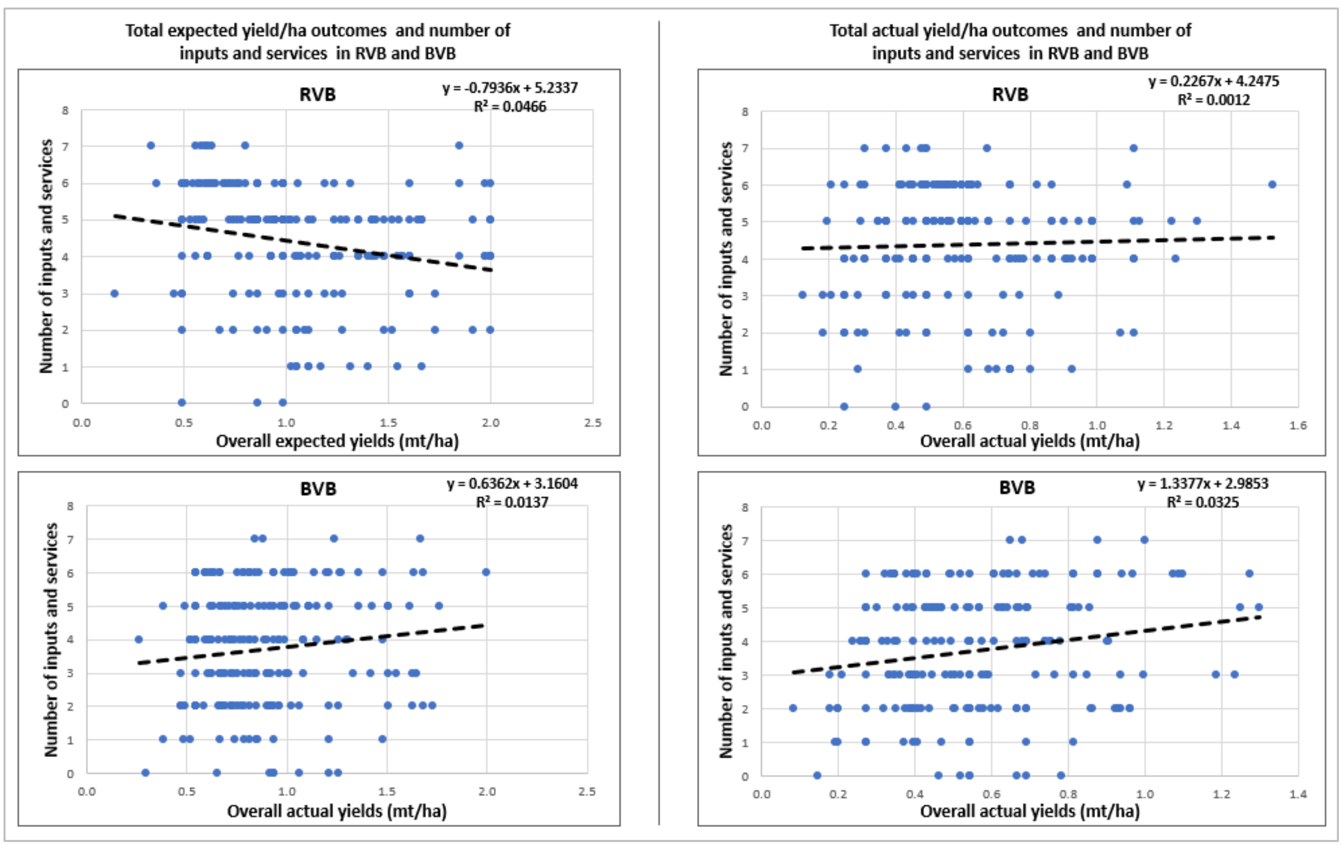

Figure 16: *Scatter plots showing the relationship between crop yield/ha (expected and actual) and the number of adopted on-farm strategies in RVB and BVB.*

5.3.2.2 On-farm strategies and respondents' community, age and education

Pearson's t-test and Chi-square results show that adopting some on-farm water, soil and crop management strategies differ based on respondents' community, age category and educational level in both RVB and BVB. See **Table 29** below and ***Appendix G (vi)*** for details.

At the community level, t-test results indicate that respondents in communities with water sources are likely ($p \leq 0.05$) to adopt more on-farm strategies than communities without water sources in RVB and BVB, especially for water and crop management strategies. Chi-square results show that in RVB, respondents in communities with water sources (Vea) are more likely ($p \leq 0.05$) to practice irrigation, water harvesting, mulching, chemical fertiliser use, pest/disease control, sowing in rows and seed testing than those without (Beo and Lungu). However, in BVB, irrigation, chemical fertiliser use, and pest/disease control are more common on-farm management strategies among respondents in communities with water sources (Mettow) than those without water sources (Zambo and Yagture). Also, even though irrigation is common in communities with water sources in both basins, respondents in Vea/RVB (77%) are more likely than those in Mettow/BVB (46%) to adopt the strategy. Irrigation along the Vea dam is more established than along the Black Volta River, making irrigation in Vea more robust than in these communities. Nevertheless, respondents in BVB and RVB without water sources are more likely to adopt improved seeds (drought resistant) than those with water sources. Communities without water sources practice rainfed farming and rely on drought-resistant crops against erratic rainfall and dry spells.

For the age category, t-test analysis shows that younger ($\leq$ 40 years) are more likely than older respondents to use more water, soil and crop management strategies in RVB and BVB. Chi-square results indicate that younger respondents in RVB are more likely ($p \leq 0.05$) to adopt improved seeds, mulching, chemical fertiliser use, sowing in rows and seed testing than older respondents. In BVB, younger are more likely ($p \leq 0.05$) to adopt improved seeds, water harvesting, irrigation, chemical fertiliser use, pest/disease control and sowing in rows than older respondents. Some water and crop management strategies, including water harvesting, irrigation and pest/disease control, could be labour-intensive strategies that more youthful farmers can practice.

For education, t-test results show that educated respondents in RVB ($p = 0.02$) are likely to adopt more on-farm management strategies than less-educated, while in BVB, the number of adopted on-farm strategies is similar ($p > 0.05$) among respondents regardless of educational status. Chi-square results show that educated respondents in RVB are more likely to adopt improved seeds, chemical fertiliser use, organic manure and sowing in rows than less-educated respondents. However, even though education is not a determinant of overall on-farm management strategies adopted in BVB, more educated are likely to adopt improved seeds and irrigation as water management strategies than less-educated respondents. Educated farmers may have more access to information and extension services than less-educated farmers, enabling them to increase their adoption of some on-farm management strategies.

Table 29: *Chi-square results comparing the associations (p-values) within communities, age and education categories for on-farm management adoptions in RVB and BVB.*

Categories	On-farm Adoption	Pearson's Chi-Square P-Value					
		Community		Age		Education	
		RVB	*BVB*	*RVB*	*BVB*	*RVB*	*BVB*
Water management strategies	Improved seeds	0.04*	0.041*	0.036*	0.049*	0.006*	0.025*
	Water harvesting	0.011*	0.922	0.368	0.032*	0.038*	0.366
	Irrigation	<0.001*	<0.001*	0.236	0.04*	0.335	0.049*
	Mulching	0.04*	0.744	0.038*	0.146	0.509	0.564
Soil management strategies	Chemical fertilisers	0.009*	0.032*	0.048*	0.004*	0.049*	0.809
	Leguminous crops	0.34	0.424	0.551	0.268	0.5	0.276
	Organic matter	0.502	0.868	0.288	0.528	0.049*	0.924
	Soil erosion	0.803	0.661	0.032*	0.16	0.396	0.933
	Crop rotation	0.578	0.569	0.171	0.569	0.169	0.213
Crop management strategies	Pest/disease control	0.043*	0.04*	0.308	0.038*	0.736	0.592
	Sowing in rows	0.008*	0.222	0.006*	0.044*	<0.001*	0.372
	Mixed cropping	0.856	0.575	0.192	0.482	0.975	0.676
	Seed testing	0.034*	0.577	<0.001*	0.158	0.464	0.118

" denotes significance level <= 0.05"*

These analyses indicate that communities without water sources and dependent on rainfed farming are vulnerable to water-related risks and may require support to boost water management, especially in BVB. Younger and educated farmers are more likely to increase the adoption of strategies than elderly and less-educated farmers, especially in RVB.

5.3.2.3 Gender influence on the adoption of on-farm strategies

Pearson's t-test and Chi-square analysis show that the pattern of adopted on-farm management strategies differs between males and females in BVB ($p \leq 0.05$) but is similar in RVB ($p > 0.05$). See **Table 30** below and **Appendix G** for details.

T-test results indicates that males are more likely ($p < 0.001$) than females to adopt more water, soil and crop management strategies in BVB, while the number of on-farm strategies adopted is similar ($p > 0.05$) across genders in RVB. Chi-square results indicates that males are more likely than females ($p \leq 0.05$) to adopt improved seeds, irrigation, mulching, water harvesting, chemical fertiliser use, erosion control, pest/disease control and sowing in rows in BVB. Women group in an FGD in Mettow explained that access to arable land for dry season farming is hard, and when accessible, they require intensive resources (labour and capital) to develop, which are often unavailable. However, females in BVB are more likely than males to adopt organic matter use and mixed cropping as on-farm management strategies. High female adoption of organic matter in BVB could likely be due to inadequate access to chemical fertilisers, compelling them to rely on compost/organic manure. In 2020, about 95% of 1,515 bags of subsidised NPK/UREA fertilisers supplied in BVB went to male farmers, leaving only 5% for farmers (DOA-Lawra, 2020). However, 64% of farmers trained in compost making were females, while 36% were male farmers (See ***Appendix F(i)***). Also, adopting mixed cropping could be due to household food needs, where female farmers often mix cereals with vegetables like pepper or legumes to increase food options.

In RVB, besides mixed cropping ($p \leq 0.05$), males and females adopt on-farm water, soil and crop management strategies. Inputs like chemical fertiliser in RVB are predominantly through government subsidies and are often available to both male and female farmers. Also, more females in RVB were selected for training on various irrigation strategies than their male counterparts a year before the survey. See ***Appendix F(i)***. Males and females in RVB adopt similar crop management strategies, likely due to high access to extension services and inputs. For instance, in 2020, more females in RVB (48%) received agrochemicals for pest/disease control than BVB (26%). See ***Appendix F(ii)***.

Table 30: *Chi-square results comparing the associations (p-values) within gender categories for on-farm management adoptions in RVB and BVB.*

Categories	On-farm Adoption	Chi-Square P-value Gender	
		RVB	***BVB***
Water management strategies	Improved seeds	0.403	0.016*
	Water harvesting	0.225	0.003*
	Irrigation	0.516	<0.001*
	Mulching	0.486	<0.001*
Soil management strategies	Chemical fertilisers	0.868	0.047*
	Leguminous crops	0.18	0.185
	Organic matter	0.119	0.049*
	Soil erosion	0.647	0.027*
	Crop rotation	0.427	0.654
Crop management strategies	Pest/disease control	0.868	0.004*
	Sowing in rows	0.551	0.022*
	Mixed cropping	0.041*	0.25
	Seed testing	0.236	0.385

" denotes significance level <= 0.05"*

5.3.2.4 Socioeconomic determinants of adopted on-farm management strategies

Cropland size, access to inputs/services, farm expenditure, expected yields/ha and actual yields/ha are used as independent variables in an ordinal logistic regression analysis to predict the number of on-farm strategies (dependent variables) adopted in RVB and BVB. See **Table 31** below.

All other independent variables (except for expected yields) influence ($p \leq 0.05$) the number of on-farm management strategies adopted in RVB (R^2 = 0.305) and BVB (R^2 = 0.17). In RVB, respondents' cropland size increases with decreasing number of on-farm strategies than in BVB, where farmland size increases with the number of on-farm strategies. These results suggest that farmers with bigger cropland in RVB adopt fewer on-farm strategies than farmers with smaller farms, while in the BVB, farmers with bigger farms adopt more strategies than farmers with smaller farms. Vulnerable farmers with small farms in RVB may try different strategies to reduce biophysical risks even though they may not be effective. The access to inputs/services and expenditures increases with the number of on-farm management strategies in RVB and BVB. These results mean access to inputs/services and investment can increase adoption in RVB and BVB.

Interestingly, respondents' actual yields/ha increase with fewer management strategies in RVB and BVB. This result signals that increasing adopted strategies does not necessarily lead to high productivity. Vulnerable farmers with smaller farms who may try many strategies have fewer actual yields/ha, likely due to the inadequate capital to invest in a few essential strategies, often provided through expert advice from AEA, NGOs or Input suppliers.

Table 31: *Comparing multiple regression p-value and Beta results of socioeconomic determinants and on-farm strategies adoption for RVB and BVB.*

		RVB		BVB	
	Variables	**Estimate**	**p-value**	**Estimate**	**p-value**
1	*Cropland size (ha)*	-0.122	0.011*	0.231	0.028*
2	*Inputs access*	2.558	0.01*	0.708	0.049*
3	*Services access*	3.56	<.001*	1.636	0.002*
4	*Expenditure*	0.002	0.011*	0.001	0.011*
5	*Expected yields*	-0.301	0.431	0.471	0.429
6	*Actual actual yields*	-0.968	0.05*	-1.235	0.05*
	Dependent variable: Number of adopted on-farm strategies				

" denotes significance level <= 0.05"*

5.3.2.5 Biophysical risk perceptions as determinants of adopted on-farm strategies

Pearson's correlation tests the overall relationship between biophysical risk and on-farm adoption. At the same time, chi-square and binary logistic regression are combined to test the strength of the association between respondents' individual biophysical risk perceptions and the on-farm strategies.

Pearson's correlation analysis shows a positive relationship in RVB ($r = 0.351$, $p = 0.001$) and a negative relationship in BVB ($r = - 0.364$, $p < 0.001$) between biophysical risks perception and adopted on-farm management strategies. The positive relationship in RVB indicates that respondents' perception of biophysical risks increases with adopting more on-farm strategies. However, the negative relationship in BVB indicates that respondents' perception of biophysical risks decreases with adopting fewer on-farm strategies. The different outcomes from both basins may be that while respondents in RVB take more action against perceived biophysical risks, those in BVB take less action to reduce these risks.

Variables found to have significant associations in chi-square tests (**Table 32** below) are used in binary logistic regression analysis (**Table 33** below) to determine which specific biophysical risk perceptions could better predict on-farm strategy adoptions. Some of the interesting outcomes show that for water management, respondents in RVB who adopt improved seeds are more likely ($p \leq 0.05$) to perceive disease occurrence (DO) as a maximum risk. However, in BVB, those who do not adopt improved seeds are more likely ($p \leq 0.05$) to perceive changing planting dates (CPD) as a maximum risk to crop production. Also, respondents who do not adopt irrigation are more likely ($p \leq 0.05$) to perceive scarce water for irrigation (SWI) in RVB, and erratic rainfall (ER) and limited soil moisture (LSM) in BVB as maximum risks to crop production.

For soil management, respondents who do not adopt chemical fertiliser are more likely ($p \leq 0.05$) to perceive depleted soil nutrients (DSN) in RVB and dry spells (DS) in BVB as maximum risks. Also, respondents who adopt crop rotation in RVB are more likely ($p \leq 0.05$) to perceive DSN as a maximum risk. In BVB, those who do not adopt erosion control are more likely ($p \leq 0.05$) to perceive poor organic matter content (POMC) as a maximum risk. Respondents who adopt pest/disease control in RVB perceive disease occurrence as a maximum risk, while those in BVB who adopt seed testing perceive pest and disease occurrence as maximum risks.

These results suggest that more respondents from RVB who adopt on-farm strategies do so based on the severity of biophysical risks, while more of those in BVB who are impacted by biophysical risks do not adopt any response to mitigate these risks. The vast extension access in RVB enables institutions to assist vulnerable farmers (respondents with maximum risk perception) to increase their capacity to adopt more on-farm strategies to reduce biophysical risks. This outcome re-emphasises the earlier findings that showed that respondents with small cropland sizes also increase their on-farm strategies (see **Table 31** above).

Table 32: *Chi-square results comparing the p-values between individual biophysical risk perceptions and individual adopted on-farm strategies in RVB and BVB.*

			Water-related Risks (p-values)						Soil-related Risks (p-values)				Crop-related Risks (p-values)	
	Strategies	Basin	ER	IT	DS	CPD	SWI	SF	DSN	LSM	SE	POMC	PO	DO
Water Strategies	Improved seeds	RVB	0.23	0.012	0.025	0.049	0.89	0.12	0.68	0.91	0.04	0.23	0.67	0.002
		BVB	0.5	0.34	0.45	0.038	0.1	0.37	0.456	0.025	0.023	0.6	0.039	0.68
	Water harvesting	RVB	0.001	0.14	0.0452	<0.001	0.05	<0.001	<0.001	0.67	<0.001	0.8	0.001	0.001
		BVB	0.051	0.22	0.51	0.09	0.05	<0.001	0.005	0.006	0.38	0.002	0.006	0.019
	Irrigation	RVB	0.08	0.44	0.094	0.078	<0.001	0.026	0.007	0.006	0.05	0.046	0.088	0.7
		BVB	0.005	0.077	0.051	0.095	0.048	<0.001	0.8	0.025	0.05	0.075	0.09	0.86
	Mulching	RVB	0.013	0.077	0.013	0.05	0.053	0.041	0.002	0.9	0.046	0.9	0.007	0.51
		BVB	<0.001	0.34	0.11	0.56	0.018	0.007	0.037	<0.001	0.043	0.048	0.45	0.08
Soil Strategies	Chemical fertilisers	RVB	0.003	0.55	0.069	0.031	0.045	0.7	0.04	0.05	0.63	0.0456	0.085	0.05
		BVB	0.001	0.086	0.026	0.04	0.045	0.2	<0.001	0.04	0.44	<0.001	0.82	0.08
	Leguminous crops	RVB	<0.001	<0.001	0.14	0.34	0.5	0.09	0.24	0.44	0.16	0.071	<0.001	0.017
		BVB	0.76	0.5	0.05	0.09	0.7	0.011	0.14	0.34	0.07	0.87	<0.001	0.34
	Organic matter	RVB	0.45	0.8	0.88	0.078	0.6	0.3	0.12	0.52	0.34	0.34	0.045	0.14
		BVB	0.08	0.51	0.044	0.095	0.14	0.11	0.44	0.94	0.55	0.55	0.7	0.22
	Soil erosion	RVB	0.001	0.08	0.7	0.02	0.08	0.09	0.7	0.07	0.6	0.077	0.052	0.44
		BVB	<0.001	0.18	<0.001	0.05	0.045	0.005	<0.001	<.001	<0.001	<0.001	0.5	0.077
	Crop rotation	RVB	0.048	<0.001	<0.001	0.34	<0.001	<0.001	<0.001	<0.001	<0.001	0.001	0.12	0.34
		BVB	0.45	0.0481	0.014	0.14	0.55	0.8	0.04	0.37	0.46	0.017	<0.001	0.025
Crop Strategies	Pest/disease control	RVB	0.003	0.044	0.7	0.7	0.8	0.74	0.4	0.12	0.05	0.007	0.04	0.026
		BVB	<0.001	0.04	<0.001	0.14	0.019	0.007	0.005	<0.001	0.33	0.007	0.04	0.04
	Sowing in rows	RVB	0.54	0.65	0.03	0.7	0.011	0.65	<0.001	0.05	<0.001	0.002	0.7	0.04
		BVB	0.016	0.08	0.4	0.84	0.08	0.51	0.91	0.05	0.93	0.48	0.33	0.0455
	Mixed cropping	RVB	0.017	0.51	<0.001	<0.007	0.11	0.88	<0.001	0.013	0.07	0.4	0.1	0.14
		BVB	0.89	0.08	0.89	0.82	0.0455	0.1	0.09	0.15	0.09	0.32	0.99	0.34
	Seed testing	RVB	0.07	0.18	0.078	0.18	0.05	0.004	0.078	0.3	0.02	0.44	0.23	<0.001
		BVB	0.80	0.32	0.68	0.91	0.67	0.23	0.095	0.98	0.49	0.077	0.04	0.03

P ≤ 0.05: Respondents who *did not adopt* an on-farm strategy and perceived biophysical risk as "maximum risk" | ***P ≤ 0.05:*** Respondents who ***adopted*** an on-farm strategy and perceived biophysical risk as "maximum risk". **Biophysical Risks:** Erratic Rainfall **(ER)**, Increased Temperature **(IT)**, Changing Planting dates **(CPD)**, Scare Water for Irrigation **(SWI)**, Severe Floods **(SF)**, Depleted Soil nutrients **(DSN)**, Limited Soil Moisture **(LSM)**, Soil Erosion **(SE)**, Poor Organic Matter Content **(POMC)**, Pest Occurrence **(PC)** and Disease Occurrence **(DC)**.

Table 33: *Logistic regression results comparing the biophysical risk perceptions that could predict the adoption of on-farm strategies between RVB and BVB.*

			Water-related Risks (p-values)						Soil-related Risks (p-values)				Crop-related Risks (p-values)	
	Strategies	Basin	ER	IT	DS	CPD	SWI	SF	DSN	LSM	SE	POMC	PO	DO
Water Strategies	Improved seeds	RVB												0.05
		BVB				0.027								
	Water harvesting	RVB	0.032						0.003		<0.001			
		BVB					0.05	<0.001		0.008				
	Irrigation	RVB					<0.001							
		BVB	0.05					<0.001		0.025				
	Mulching	RVB	0.04										0.049	
		BVB	<0.016				0.05	0.01		0.012				
Soil Strategies	Chemical fertilisers	RVB					0.021		0.05					0.05
		BVB	0.012		0.05									
	Leguminous crops	RVB												
		BVB			0.027								0.05	
	Organic matter	RVB												
		BVB			0.044									
	Soil erosion control	RVB												
		BVB	<0.001					<0.001		<0.022		0.05		
	Crop rotation	RVB	0.004	0.041	<0.001			0.029	0.019					
		BVB		0.002	0.018							0.015	<0.011	
Crop Strategies	Pest/disease control	RVB												0.05
		BVB	0.005		0.05		0.05							
	Sowing in rows	RVB					0.003		0.024					0.010
		BVB	0.05							0.003				0.047
	Mixed cropping	RVB												
		BVB												
	Seed testing	RVB												<0.001
		BVB											0.05	<0.001

P ≤ 0.05: Respondents who *did not adopt* an on-farm strategy and perceived biophysical risk as "maximum risk" | ***P ≤ 0.05:*** Respondents who ***adopted*** an on-farm strategy and perceived biophysical risk as "maximum risk". **Biophysical Risks:** Erratic Rainfall **(ER)**, Increased Temperature **(IT)**, Changing Planting dates **(CPD)**, Scare Water for Irrigation **(SWI)**, Severe Floods **(SF)**, Depleted Soil nutrients **(DSN)**, Limited Soil Moisture **(LSM)**, Soil Erosion **(SE)**, Poor Organic Matter Content **(POMC)**, Pest Occurrence **(PC)** and Disease Occurrence **(DC)**.

5.3.3 Determinants of perceived effective on-farm strategies

Access to agriculture advisories, information, extension services and FBOs are used as independent variables in a multiple linear regression analysis to predict the perceived effectiveness/efficiency (average) of adopted on-farm strategies in RVB and BVB, as shown in **Table 34** above. These independent variables can enable the effective adoption of on-farm strategies, which could increase yields. Overall, the model could predict 34% of the variance in on-farm strategies in RVB and 25% in BVB.

Table 34: *Comparing regression p-value and Beta (β) results for determinants of effective management strategies in RVB and BVB.*

	Independent variables	Red Volta		Black Volta	
		β	p-value	β	p-value
1	Expert Advisory	.287	.001	.037	.699
2	Access to information	.351	.000	.380	.000
3	Access to extension	.211	.018	.040	.630
4	FBO participation	.181	.010	.050	.415

Significance level ($p \leq 0.05$)

The perceived effectiveness/efficiency of adopted on-farm strategies increases with access to expert advice, information, extension, and FBO in RVB. However, in BVB, all the independent variables (except for access to information) could not determine/predict ($p > 0.05$) the effectiveness of on-farm strategies. The low extension service in BVB (55%) than RVB (91%) could explain the outcome between basins. Extension services facilitate access to information, expert advice, and FBO in RVB and BVB. As shown in **Table 35** below, DOA in RVB exceeded targets for extension services for 2019 and 2020 compared to BVB. In a KII, an AEA in BVB claimed that the low AEA to farmer ratio and the inadequate logistics are reasons for the low extension delivery in the area.

Table 35: *Comparing the number of farmers who benefited from farm demonstrations in 2019 and 2020 for RVB and BVB.*

Year	RVB				BVB			
	Target	Reached	Males	Females	Target	Reached	Males	Females
2019	4000	4992	1996	2996	550	280	84	196
2020	4000	4518	1592	2926	550	123	59	64

Source: (DOA-Bongo, 2020; DOA-Lawra, 2020).

5.3.3.1 Effectiveness of on-farm strategies and crop productivity

Further multiple linear regression analysis indicates that expected yields/ha and actual yields/ha in RVB ($R^2 = 0.15$) and BVB ($R^2 = 0.10$) could predict ($p \leq 0.05$) the perceived effectiveness of on-farm strategies. See **Table 36** below. Perceptions of effective/efficient on-farm strategies increase with expected yields/ha while decreasing with actual yield/ha in RVB and BVB. These results suggest that the perception of on-farm strategies as effective increases their expectations of higher yields but may not always lead to increasing actual yields.

However, adopting effective/efficient strategies through expert advice could increase actual yields/ha in RVB and BVB. The Multiple linear regression test shows that an increase in expert advisories on adopted on-farm strategies increases actual yields/ha in RVB and BVB, as shown in **Table 36** below. An AEA in RVB explained that farmers who receive advice throughout the production cycle have increased yields.

"In my ten years as an AEA, proactive farmers seeking advice before the farming season have better yields than those who wait until later when biophysical risks escalate. At that point, we can do little or nothing to recover the damage".

- AEA, RVB

Table 36: *Multiple linear regression shows expected and actual yields/ha as predictors of the effectiveness of on-farm strategies and expert advice.*

Dependent variables	Basin	Independent Variables	Unstandardized Coefficients (B)	t	p-value
Effectiveness of on-farm strategies	RVB	*Expected yield/ha*	0.448	5.84	<.001*
		Actual yield/ha	-0.478	-3.097	0.002*
	BVB	*Expected yield/ha*	1.058	2.969	0.003*
		Actual yield/ha	-1.011	-2.054	0.041*
No. of adviosries on on-farm startegies	RVB	*Expected yield/ha*	-0.781	-1.476	0.142
		Actual yield/ha	2.568	2.402	0.017*
	BVB	*Expected yield/ha*	-2.523	-1.794	0.084
		Actual yield/ha	3.605	1.842	0.05*

" denotes significance level <= 0.05"*

5.3.4 Determinants of access to experts' advice

Access to extension services, information, FBOs, radio and mobile phone, as well as the gender of respondents, are used as independent variables in a binary logistic regression analysis to predict expert advice (dependent variable) in RVB and BVB. The analysis showed that the independent variables could explain 45% of the variance in expert advice in RVB and BVB. Except for gender and FBO, access to information ($p = 0.011$), extension ($p < .001$), mobile phone ($p = .020$) and radio ($p = .050$) can determine access to expert advice in RVB. In BVB, respondents with access to information ($p < .001$), extension ($p < .001$), FBOs ($p = .018$) radio ($p = 0.35$) could predict expert advice than gender and mobile phone. These results suggest that expert advice enables the transfer, sharing and exchange of knowledge and information through extension, FBOs, radio and mobile phones.

However, Pearson's t-test analysis shows that the number of expert advisories received in RVB differs among respondents based on their access to FBO ($p = 0.05$), information ($p = 0.038$), extension ($p < 0.001$), radio ($p = 0.006$) and mobile phone ($p = 0.031$). Respondents with access to FBO, information, extension, radio and mobile phone are more likely to receive expert advice. In BVB, the results showed that the number of expert advisories received for on-farm strategies differs across gender ($p = 0.017$), FBO participation ($p = 0.007$), access to information ($p < 0.001$), extension services ($p < 0.001$) and mobile phone ($p = 0.05$). Male farmers who belong to FBOs, access agriculture information, receive extension services, and have mobile phones are more likely to receive expert advice than those outside these categories.

5.3.4.1 Experts' Advice as a determinant of adopted on-farm strategies and their perceived effectiveness

Pearson's Chi-square test is used to determine whether respondents who receive expert advice are associated with adopted on-farm strategies and effectiveness in RVB and BVB, as shown in **Table 37** below.

In RVB, the results indicated that respondents who receive expert advice are more likely ($p \leq 0.05$) to adopt most on-farm strategies, besides improved seeds, soil erosion control and crop rotation, than those without. However, respondents' access to expert advice could not be associated ($p > 0.05$) with perceived effectiveness for most adopted strategies besides water harvesting and soil erosion control.

In BVB, respondents who access expert advice are more likely ($p \leq 0.05$) to adopt most on-farm strategies, apart from irrigation, mulching, leguminous crops and pest/disease control, than those without. Also, those who receive expert advice consider most of their adopted on-farm strategies as effective ($p \leq 0.05$) besides water harvesting, soil erosion, irrigation, mulching and seed testing.

The possible reason expert advice is associated with adoption and not effectiveness in RVB for most on-farm strategies could be the high access to extension services within the basin where advice often goes along with extension services, as discussed earlier. However, the outcome in BVB could be due to low extension services and that farmers with access to extension services also have access to expert advice support that could enable the effective adoption of most on-farm strategies.

Table 37: *Chi-square results comparing the p-values between on-farm advisory and adopted on-farm strategies/perceived effectiveness in RVB and BVB.*

Category	On-farm Advisory	Pearson's Chi-square p-values			
		Adoption		Effectiveness	
		RVB	***BVB***	***RVB***	***BVB***
Water management	Improved seeds	0.231	0.04*	0.438	0.018*
	Water harvesting	<0.001*	0.029*	<0.001*	0.598
	Irrigation	<0.001*	0.132	0.129	0.42
	Mulching	<0.001*	0.605	0.745	0.52
Soil management	Chemical fertilisers	0.001*	<0.001*	0.514	<0.001*
	Leguminous crops	<0.001*	0.751	0.783	0.003*
	Organic matter/manure	<0.001*	0.186	0.927	0.003*
	Soil erosion control	0.701	0.009*	0.017*	0.129
	Crop rotation	0.747	0.047*	0.815	<0.001*
Crop management	Pest/disease control	<0.001*	0.477	0.256	0.024*
	Sowing in rows	0.004*	<0.001*	0.669	0.026*
	Mixed cropping	<0.001*	<0.001	0.934	0.05*
	Seed testing	<0.001*	<0.001*	0.682	0.471

" denotes significance level <= 0.05"*

In summary, the decision to adopt on-farm strategies appears to depend on the strategy type, as well as farmers' demographic and socioeconomic characteristics. Expected and actual yield/ha reduces with an increasing number of on-farm strategies, especially in RVB. However, the number of on-farm strategies adopted through expert advice increase their effectiveness and actual yield/ha in RVB and BVB. Respondents in communities with water sources and younger respondents are more likely to adopt more water management strategies in RVB and BVB. Also, young and educated respondents are more likely to adopt more soil and crop management strategies in both RVB and BVB. However, males in BVB are more likely than females to adopt more water, soil and crop management strategies. At the same time, adoption between males and females is similar in RVB. Biophysical risk perceptions, farm size, expenditure, inputs/service and farmland size determine the adoption of on-farm strategies in RVB and BVB. In contrast, access to information, extension and FBO could determine effective strategies and expert advice in both basins, especially in RVB.

5.4 Discussion: Biophysical characteristics as enablers of SI goals/principles

This chapter aims to assess and compare the biophysical determinants of crop productivity as enablers or barriers to SI goals in semi-arid smallholder crop production systems in RVB and BVB of Northern Ghana. The themes for discussion are the SI principles of productivity, resilience, efficiency, and equity, as described in the conceptual framing. The goal is to know how farmers' biophysical characteristics, including perceptions and adopted on-farm strategies hinder or enhance productivity, resilience, efficiency and equitable use of biophysical properties (water, soil, ecosystems and crop health). This section discusses the study's key findings alongside evidence from previous literature in Northern Ghana and their implications for SI. Based on the key findings, practical recommendations are made for Policy, practice, and research to achieve SI goals in Northern Ghana and West Africa.

5.4.1 Impact of perceived biophysical risks and implications for crop productivity

Past literature agrees on the threats biophysical risks pose to crop production in semi-arid areas of West Africa (Padgham et al., 2015; Sultan & Gaetani, 2016). The findings from the present study corroborate what is known in the existing literature about farmers' perceptions of water, soil, ecosystem, and crop health-related risks that determine their productivity in RVB and BVB.

The findings on water-related risks revealed that farmers in RVB are more likely than those in BVB to perceive the overall water-related risk as a threat to crop production. However, erratic rainfall, high temperatures, dry spells, changing planting dates, and scarce water for irrigation are perceived in both basins as high-risk factors for crop productivity. Specifically, farmers who perceive increased temperature in RVB and dry spells in BVB as high-risk factors to their farming also had lower yields. Evidence from previous literature shows that farmers in Northern Ghana generally perceive water-related risks, including rainfall, temperature, dry spells and changing planting dates, as threats to crop production (Lawson et al., 2020; Nyantakyi-Frimpong & Bezner-Kerr, 2015). Farmers' perceptions of water-related risks may worsen as climate change impacts water resources within semi-arid regions of West Africa. As the impact of climate change on water resources intensifies, farmers will need adaptation options, such as irrigation, to minimise impacts on rain-fed agriculture (A. Niang et al., 2017; I. Niang et al., 2015; Worqlul et al., 2019).

In line with previous research conducted in Northern Ghana, farmers in RVB and BVB acknowledge soil-related risks as significant threats to their crop production, notably depleted soil nutrients, low soil moisture, and poor organic matter. However, farmers in RVB viewed soil-related risks as more significant threats to crop productivity than farmers in BVB. Specifically, those farmers in RVB who considered depleted soil nutrients a major risk factor were found to have lower crop yields. Various studies have shown that soil properties in West Africa enhance crop productivity (Crane et al., 2011; A. Niang et al., 2017); however, due to the poor nature of semi-arid soils, Tanaka et al. (2013) could not establish its significant role in boosting crop productivity without fertilisation. Surprisingly, some of the findings contradict previous studies in Northern Ghana. For instance, even though the present study found that soil erosion is perceived as a low-risk factor among farmers in both basins, previous work by Tesfahunegn et al. (2021) shows that farmers in Northern Ghana generally perceive soil erosion as a serious risk to crop production. The possible reason for the conflicting evidence could be the different local contexts and sample groups of both studies. These findings reinforce the importance of addressing soil-related issues in the region to ensure the sustainability of crop production.

On perceived ecosystem-related risks, the study found that they were the least threatening compared to other biophysical risks in both basins. Nevertheless, farmers in RVB tend to perceive deforestation, charcoal/firewood production, and bushfires as less threatening to the agriculture system than those in BVB. Implementing by-laws reduced environmental degradation for communities in both basins; however, these actions were more effective in RVB. Boafo et al. (2016) found that traditional ecosystem management through rules and regulations, taboos and totems, and customs and rituals enable the efficient use of ecosystem services in some communities in Northern Ghana. Interestingly, farmers from sampled communities in BVB (Mettow, Zambo, and Yagture) perceived ecosystem-related risks differently, while those in RVB communities (Vea, Lungu, and Beo) had similar perceptions. For instance, most farmers in the Zambo community in BVB perceived deforestation and bushfire as high-risk factors that could destroy soil properties for farming more than farmers in Mettow/Yagture communities. Communities affected by ecosystem risks could be due to poor capacity to manage ecosystems or less compliance with the by-laws set up to regulate the use of ecosystem services (Boafo et al., 2016).

The findings regarding the perceived crop health-related indicate that although pest and disease infestations are serious problems for both basins, farmers in RVB are more likely to view them as major risks to their crop production than those in BVB. This finding is consistent with what Koffi et al. (2021) found in the Sudan Savanna (RVB), where the impact of FAW was more severe than in other parts of the country.

Additional significant findings indicate that factors such as cropland size and the availability of inputs and services can impact farmers' views of biophysical risks in RVB and BVB. Farmers with bigger cropland (≥ 2ha) tend to perceive biophysical risks as high-risk factors to crop production than those with smaller cropland (< 2ha). Due to more resources (labour and capital) needed to cultivate larger cropland, farmers with more than 2 hectares are affected more by dry spells, erratic rainfall, and degraded soils. Deressa et al. (2011) noted that farmers with extensive farms respond negatively to climatic risks due to more resources needed for on-farm adaptation. Also, farmers in BVB with limited access to input and services tend to perceive biophysical risks as threats to their framing activities more than those in RVB. Previous case studies in Northern Ghana found that access to agricultural resources increases climate change adaptation efforts by reducing biophysical risks (Ahmed et al., 2016; Tesfahunegn et al., 2021).

5.4.2 Adoption of on-farm strategies as resilience to biophysical risks

Although biophysical risks threaten crop production in semi-arid West Africa, previous research has demonstrated various strategies farmers adopt to build resilience (Partey et al., 2018; Zougmoré et al., 2016). The findings of the present study have shown similar trends in the adoption of on-farm water, soil, and crop management strategies, as well as other adaptation and coping mechanisms, to enhance resilience and manage biophysical risks in RVB and BVB.

The study's findings show that although water-related risks threaten crop production, few farmers in both basins adopted water management strategies. However, farmers in RVB are more likely to adopt irrigation and improved seeds, while those in BVB tend to adopt munching to manage erratic rainfall and dry spells. Multiple sources support this finding as records show that certified seed supply and irrigation activities in the RVB area are more than that of BVB (DOA-Bongo, 2020; DOA-Lawra, 2020; Namara et al. al., 2011). Farmers in communities with water sources in both basins tend to practice irrigation and water harvesting more than those without water sources which rely on improved seeds (drought-resistant varieties) for rain-fed farming. These findings are consistent with a study in RVB, which identified households closer to the Vea dam engage in dry season irrigation farming and aquaculture, while those further away from the dam often relied on improved seeds and off-farm activities to reduce water stress (Yomo et al., 2020).

Unlike water management strategies, most farmers in both basins have adopted soil management strategies to manage soil-related risks. Nevertheless, farmers in RVB are more likely than BVB to adopt leguminous crops, organic matter/compost, and erosion control (stone bone and ridges) as soil management techniques. DOA 2020 reports suggest that the percentage of farmers in RVB who received training on soil improvement strategies, including compost making, intercropping, and stone bonding, was more than those in BVB (DOA-Bongo, 2020; DOA-Lawra, 2020). On the contrary, farmers in BVB are more likely than RVB to use chemical fertilisers and crop rotation techniques to improve degraded soils. Nevertheless, overuse of chemical fertiliser can affect the nutrient cycle and lead to maladaptation (Robinson et al., 2015). The low population density in BVB than RVB makes it possible for farmers to access extra croplands to practice crop rotation and bush fallow as a soil management strategy. Farmers in BVB tend to adopt chemical fertilisers more than those in RVB, possibly due to easy access to inputs from retailers than through subsidies from government programmes, which often delays.

Crop health management at every stage of the cropping system is critical for building resilience in the present study. The results show that except for seed testing, most farmers in both basins practice sowing in rows, pest/disease control, and mixed cropping as crop management techniques as on-farm coping mechanisms against pests and disease infestation. However, farmers in RVB are more likely to adopt pest/disease control and mixed cropping than BVB. Adopting pest/disease control and planting in rows in RVB were found useful in increasing farmers' yields. Evidence from several sources supports the findings indicating that farmers with access to frequent pest/disease control training can manage the high pest (FAW) infestation to reduce the risks of crop failure (Adu et al., 2014; Tanzubil, 2016).

Unlike water, soil and crop health strategies, ecosystem management is practised in the community as a collective action than at the individual farm level. The present results showed that farmers in BVB are more likely than those in RVB to participate in capacity training for land reclamation, reafforestation, harvesting of firewood, and bushfire prevention. Since ecosystem protection is not a priority at the farm level, traditional authorities, in collaboration with local institutions, use community by-laws to enforce the rules and regulations around ecosystem management at the community level. These rules and regulations may range from monetary fines to criminal charges depending on the seriousness of ecosystem damage caused (Boafo et al., 2016).

Other critical findings from the study show that farmers' cropland size, access to inputs/services, expenditure, actual yields/ha and biophysical risk perceptions can determine the adoption of on-farm strategies in both basins. For instance, farmers with access to more inputs/services and high expenditures tend to adopt more strategies in both basins. Evidence from Northern Ghana supports the findings by indicating that access to agricultural inputs, services, financing, land, and extension can increase farmers' adoption of on-farm strategies that enhance resilience (Boansi et al., 2017; Dakyaga et al., 2020). Surprisingly, adopting more strategies in RVB reduces yields. This finding may be due to vulnerable farmers' inability to invest in efficient strategies or practice the training received on these strategies. Dakyaga et al. (2020) explained that farmers in Northern Ghana often supplement expensive strategies with cheaper alternatives, including substituting pesticides with chicken dropping. This finding aligns with similar findings from the present study showing that farmers who perceive biophysical risks as threats to crop production tend to adopt more strategies in RVB and less in BVB. Vulnerable farmers in RVB receive support from government institutions to adopt many strategies, while those in BVB have to pay for resources from input retailers, especially fertiliser and certified seeds, to build resilience against biophysical risks. Similar findings from previous studies show that farmers' strategies to counter the effects of biophysical risks on crop production can lead to effective adaption or maladaptation (Deressa et al., 2011; Tesfahunegn et al., 2021).

5.4.3 Effectiveness and expert advice as on-farm strategy efficiency

The efficiency of on-farm strategies is identified with farmers' perceived effectiveness of on-farm strategies and their linkages with expert advice on the adoption and use of strategies. The present study found that farmers in RVB perceive most on-farm strategies as effective, while those in BVB perceive them as ineffective. The perceived effectiveness of on-farm strategies in RVB could be due to their perception of biophysical risks as threats to crop production. The findings are consistent with previous evidence, which indicated that farmers with a negative perception of their biophysical properties are more likely to practice interventions they perceive to be effective

(Deressa et al., 2011; Tesfahunegn et al., 2021). Further findings show that on-farm strategies perceived to be effective tend to increase expected yields in both basins. However, farmers' perceptions of on-farm strategies as effective do not necessarily increase actual yields unless adopted through expert advice. The study found that farmers who access expert advice to adopt on-farm strategies have higher yields than those without in both basins. For instance, farmers in RVB who receive expert advice tend to adopt irrigation and use improved seeds, while those in BVB adopt water harvesting and mulching. Previous studies in West Africa identified similar findings where farmers in Northern Ghana and Burkina Faso increased yields with extension service advice when adopting their on-farm management strategies (Boansi et al., 2017; Zougmoré et al., 2016).

Further interesting findings from the present study showed that farmers' access to information, extension, radio, mobile phone (only RVB) and FBO (only BVB) could increase their access to expert advice to enable efficient use of on-farm strategies in both basins. The channels for expert advice to farmers within the study areas include field demonstrations, one-on-one field consultations, radio events, phone calls, and advisory centres. These channels can build the capacities of farmers in both basins on essential resilient and efficient strategies for sustainable farming. The findings align with the evidence from Boansi et al. (2017) and Zougmoré et al. (2014), suggesting that farmers in semi-arid West Africa who had frequent contact with agriculture expertise increased their access to information and knowledge that enhanced their ability to adopt new technology to adapt to biophysical risks.

5.4.4 Equity perspective of biophysical risks and on-farm strategies

Previous literature has shown that farmers' demographic background, including gender, age, education and community, can determine their perceptions and response to biophysical risks (Deressa et al., 2011; Lawson et al., 2020; Nyantakyi-Frimpong, 2017). The present study identified findings similar to existing literature showing that household power dynamics and inequalities could affect farmers' perceptions of risks and adopt on-farm strategies to increase on-farm resilience, efficiency and productivity.

The present study has shown that women in RVB are more likely than men to perceive biophysical risks as threats to crop production, while the risk perceptions in BVB remain the same across genders. The findings in RVB could be due to the on-farm gender roles, where men are responsible for land preparation and women have to see to weed control, soil improvement and crop maintenance, making them more aware of the biophysical risks (Kawarazuka et al., 2020). However, men in BVB tend to adopt more on-farm management strategies to reduce risks than women, while the adoption pattern in RVB remains the same even though women have high biophysical risk perceptions than men. Previous studies found similar adoption patterns among men than women farmers and concluded that their increased access to extension services also increased their adoption of on-farm strategies more than women (Deressa et al., 2011; Tesfahunegn et al., 2021). Extension support is higher for vulnerable groups, including women in RVB, enabling a competing on-farm strategies adoption rate with men. Donkor et al. (2016) identified that access to agriculture extension services allows vulnerable farmers, predominantly women farmers, to access information that enables adopting new technologies and on-farm strategies.

Furthermore, farmers' age is essential in perceiving biophysical risks as threats in RVB and BVB. Older farmers in RVB tend to perceive biophysical risks as threats to crop production more than younger farmers, while risk perceptions in BVB remain the same across age groups, except for ecosystem risks which older farmers perceive as threats. Some studies have argued that older farmers often have more experience interacting with biophysical risks than young farmers, affecting their perception of these risks, primarily soils and ecosystems (Boafo et al., 2016; Tesfahunegn et al., 2021). Young farmers in both basins tend to adopt more on-farm management strategies than older farmers. Some evidence from Northern Ghana is similar to the findings in the study, suggesting that older farmers find it difficult to implement on-farm strategies due to the labour intensiveness of most on-farm strategies (Lawson et al., 2019; Tesfahunegn et al., 2021).

Another important finding was that educated farmers in RVB are more likely to perceive biophysical risks as threats to crop production than less-educated farmers, while education did not play any role in farmers' perception of biophysical risks in BVB. Educated farmers in RVB may be more aware of the severity of biophysical risks than less-educated, possibly due to their access to information and extension services, as noted in a study by Deressa et al. (2011). However, other evidence in Northern Ghana contradicts the findings as Tesfahunegn et al. (2021), and Koffi et al. (2021) indicated that higher education enables farmers to reduce risks associated with soil and pest, as such, they tend to consider them less threatening to farming. Even though educated farmers in RVB perceive biophysical risks as threats to productivity, the finding shows that they also tend to adopt more on-farm strategies, especially water and crop strategies, than less-educated farmers. Tesfahunegn et al. (2021) and Deressa et al. (2011) argue that educated farmers can access information and extension services to adopt new on-farm strategies and technologies that improve biophysical properties and increase crop productivity. Educated farmers with access to higher-paying off-farm jobs may reinvest part of their incomes into on-farm activities by hiring labour and other services to manage biophysical risks. Education in BVB did not impact on-farm strategies adoption, possibly because of the low extension services in the basin, which affects the adoption regardless of educational status.

Moreover, the study found that farmers' communities relative to permanent water sources (a dam or river) could influence their perception of some biophysical risks, especially in RVB. Farmers in Vea (RVB) and Mettow (BVB), closer to water sources, are less likely to perceive water scarcity as a threat to crop production due to the active dry season irrigation farming. However, farmers in Vea perceived poor organic matter content as a threat to crop production, possibly due to continuous farming on irrigated cropland throughout the year. The findings further show that communities without permanent water sources for dry season farming, especially in BVB (Zambo and Yagture), may overexploit the available ecosystem services with charcoal/firewood or timber production during the dry seasons when rainfed agriculture is inactive. Unsurprisingly, the present study shows that communities with water sources adopt more on-farm strategies than those without permanent water sources. Institutions like DOA, NGOs and input retailers often concentrate inputs and services within productive communities, especially communities with active irrigation schemes (Boansi et al., 2017; Yomo et al., 2020); as such, deepening the vulnerability of communities reliant on rain-fed farming.

Finally, the intersection between gender, age, education, and community suggests that older farmers in communities without water sources in both basins may be the most vulnerable social group, especially educated older women in RVB. This finding aligns with gender studies that suggest that women and the elderly are the most vulnerable groups impacted by climate change due to limited agricultural resources, including labour and capital (Ahmed et al., 2016; Lawson et al., 2019). On the contrary, educated young farmers in communities with water sources are the most resilient social group in RVB, while the least resilient are less-educated older farmers in communities without water sources. However, in BVB, young men in communities with water sources are the most resilient social group, while older women in communities without water sources are the least resilient. According to Yomo et al. (2020), irrigation schemes within communities in Northern Ghana often reduce farmers' vulnerability to biophysical risks, including climate change, thereby increasing adaptive capacity and resilience.

5.4.5 Implication of biophysical risks and on-farm strategies for SI in Northern Ghana

Key evidence from the present study will have implications for achieving SI goals of productivity, resilience, efficiency and equity in RVB and BVB. On productivity, the findings have shown that farmers in RVB are more likely to be affected by water, soil, and pest/disease-related risks than in BVB. Although SI has been proposed as a viable concept for sustainable farming (IPCC, 2022), the current and future biophysical risks are expected to increase the productivity challenges within semi-arid agriculture systems, hindering the efforts to implement SI. These risks result from external factors like climate change and FAW invasion coupled with localised challenges like poor soils, which affect farmers' productivity goals. For instance, climate change is expected to increase risks such as erratic rainfall, drought, severe floods and dry spells, likely affecting rainfed agriculture within smallholder farming systems in West Africa (Jalloh et al., 2012; Padgham et al., 2015). However, internal/localised risks from the continuous cropping and land expansion characterising most farming systems in West Africa exacerbate ecosystem and soil-related risks such as nutrient depletion and erosion. As the combination of biophysical risks affects crop production, farmers may be more interested in intensifying resources to increase yields rather than reducing risks to sustain productivity. Intensification without an attempt to reduce risks will only increase vulnerabilities within the crop production system in the long term and make SI difficult to achieve.

Furthermore, the study's findings have demonstrated that farmers in RVB build resilience against perceived biophysical risks by adopting more on-farm strategies than those in BVB, who tend to adopt fewer on-farm strategies. Farmers' ability to adopt and implement on-farm strategies increases resilience and enhances their capacity to reduce risks in both basins. Nevertheless, intensifying agriculture inputs to manage water resources, soil properties and pests/diseases could have an incremental impact on the agriculture system for the better or worse. Some experts have argued that the vulnerability of an agricultural system could increase when strategies implemented to reduce risks do not recognise the complex characteristics interacting within the system (Adenle et al., 2019; Robinson et al., 2015). For instance, the intensified fertiliser use in BVB and pesticides use in RVB may be useful for reducing on-farm risks but could affect water and soil quality in the long term. Increasing water withdrawals for irrigation may affect dam or river levels for users downstream. The actions needed to achieve agriculture system resilience as an SI goal require contextualising on-farm strategies at the community and household levels, where interventions seek to minimise risks and increase resilience. An effective resilience outcome is possible with agriculture system efficiency, optimising resources to achieve desired productivity and resilience goals.

Moreover, achieving efficiency within the agriculture system under SI could require using technology that supports precision farming where waste and pollution are avoided as environmental costs of intensification (Cassman & Grassini, 2020; Pham & Smith, 2014). For instance, some form of technology will be required to efficiently practice irrigation, fertilisation, seed selection, chemical application and harvesting to reduce waste and prevent resource overuse in intensification. Unfortunately, these technologies may be expensive for farmers within smallholder farming systems in RVB and BVB to afford, making some experts question the notion that technology-driven strategies are the most effective ways to achieve efficiency (Pretty et al., 2011; Snapp et al., 2018). They argue that inexpensive and less technical options should be explored for farmers to manage existing risks while increasing productivity. However, in cropping systems like RVB with high population density and large household size compared to BVB, farmers' priority will be less efficiency and more intensification to maximise food production to meet household needs. Achieving efficiency in this type of cropping system means recognising the needs of farmers and implementing strategies that create a win-win for sustainability and yield increase. Not all systems can achieve a perfect win-win in SI (Robinson et al., 2015), but an attempt to prioritise agriculture system "needs" from "wants" could enable a strategic implementation of SI in Northern Ghana.

While external and internal risks may threaten food production and sustainability, farmers' individual or household characteristics may deepen existing vulnerabilities to achieve SI productivity goals. From the present study, farmers' gender, age, education, and access to agriculture resources (inputs, information and extension), notably in RVB, could determine who may be more vulnerable or resilient to biophysical risks. Robinson et al. (2015) state that increasing farmers' overall vulnerability could make achieving a sustainable cropping system challenging, as compound risks may damage biophysical properties and affect yields. Implementing SI in Northern Ghana will require strong multilevel environmental and socioeconomic strategies that reduce vulnerabilities at the farm, household, and community levels. For instance, SI could address gender inequalities in RVB and the unequal access to services (information and extension) in BVB by focusing on equitable resource distribution that enables all social groups to address their vulnerabilities to achieve SI goals (Boansi et al., 2017; Partey et al., 2018). Equity is required for vulnerable social groups, like older women without dry season farming opportunities in both basins, to access efficient strategies to build resilience and enhance productivity. Even though the study identified young men with irrigation opportunities as the most resilient group, they may require guidance to ensure efficiency with intensification is achieved without exacerbating existing risks or depriving other social groups of thriving within the agriculture system.

5.5 Practical recommendations

5.5.1 Practice

At the community level, local institutions mandated to support farmers, including the DOA and local NGOs, should provide technical assistance for adopting water, soil and crop management strategies, especially for communities dependent on rainfed agriculture in RVB and BVB. Water management strategies, including Zai pits and half-moon, are efficient climate-smart strategies that have increased agriculture systems' resilience in a water-stressed environment like semi-arid regions (Mason et al., 2015; Partey et al., 2018; Zougmoré et al., 2016). Conservation agriculture practices, including composting, stone bunding, intercropping with legumes and mulching, are natural regeneration techniques that could be helpful for soil management among vulnerable groups such as women in BVB and the less-educated farmers in RVB. Implementing agroforestry techniques could balance productivity and ecosystem maintenance. Efficient ecosystem management needs an integrated, participatory approach that engages scientific and local knowledge to build resilience. Precision agriculture could enhance farmers' ability to increase resilience to prevent pests and diseases by taking practical actions such as seed selection/testing before sowing. Precision agriculture provides the necessary conditions for crops to grow in harsh conditions like semi-arid regions, as attention is given to the type of seeds to select, the amount of water to use, and soil nutrients required for a particular crop variety (Aune et al., 2017b; Gassner et al., 2013; Onyango et al., 2021).

These actions will require adequate resources to create awareness of biophysical risks and practical tools for inclusive participation in RVB and BVB. Community-led effort where community leaders, including chiefs and assembly members, collaborate with local NGOs and DOAs and execute biophysical risk awareness campaigns on radio, community meetings, and phone calls. Interaction between researchers and local stakeholders (practitioners) will be essential to enhance the knowledge of biophysical risks at the community level to assist farmers at the farm or household level. SI actions need to recognise vulnerabilities and inequalities among social groups and use participatory interventions to create an inclusive agriculture system regardless of gender, age, education, or community. Collaboration among institutions will be vital to achieving the SI goal of resilient and efficient strategies toward productive biophysical properties. For instance, providing dugouts and small dams can be collaborative, where local communities provide labour and institutions assist with technical knowledge on implementing effective water harvesting systems.

5.5.2 Research

Future research needs to focus on in-depth, up-to-date soil and crop research in RVB and BVB that provide farmers with a detailed report on soil and crop health-related risks at the farm or community level. The outcome could inform the specific choice of strategies needed to improve deficient soils and manage pests/disease at the farm or community level. The present research could not conduct detailed soil and crop analysis because of limited resources and time constraints. Again, future research may be required in RVB to understand why access to more inputs and services increases farmers' biophysical risk perceptions. The present research did not have enough local knowledge contributions to sustainable agriculture in RVB and BVB. We recommend this as a research gap in the present study for future investigations.

5.5.3 Policy

Local and national-level policies around biophysical properties are needed as a resource governance mechanism to enable an efficient agriculture system. Local and national stakeholders need to develop a balanced strategy that does not deprive communities of accessing ecosystem services but enhances the sustainable use and restoration of degraded ecosystems. Policy support will be needed to expand the extension and information services in BVB, enabling the adoption of critical technologies and on-farm strategies that increases resilience for crop production. Moreover, agriculture policies and programmes must emphasise equitable service distribution among social groups to achieve a resilient agricultural system in RVB and BVB. This goal is possible by increasing the number of female extension officers and extension volunteers to assist women farmers, increasing awareness and adoption, especially in BVB.

5.6 Summary

This chapter aimed to assess and compare biophysical determinants of crop productivity that could enable or hinder SI goals in RVB and BVB of semi-arid Northern Ghana, according to the aim of Objective 1. The results showed that except for ecosystem-related risks, which smallholder farmers perceived as low risks, more respondents in RVB and BVB perceived water, soil, and pest/disease-related risks as high risks to crop production. Overall, respondents in RVB were more likely to perceive biophysical risks as a threat to crop production than those in BVB. How respondents in both basins perceived their risks was consistent with biophysical constraints in Northern Ghana found in secondary sources relating to soils, ecosystems, and pests, besides water-related risks. To address the perceived biophysical risks, the study showed that respondents in RVB were more likely to adopt efficient on-farm management strategies than those in BVB.

Moreover, the empirical analysis showed that respondents who perceive biophysical risks as serious threats to crop production tend to adopt more on-farm management strategies in both basins. Respondents' gender, age, education, and community were found to influence how they perceive their biophysical risks, especially in RVB. Similarly, gender, age, education, and community were critical determinants of how respondents adopted on-farm management strategies to address perceived risks, especially in BVB. However, adopting an on-farm strategy does not necessarily lead to increased yields unless adopted with advice from farm experts. Other determinants, including access to information, extension services and FBOs, enhance awareness of biophysical risks and enable farmers to adopt efficient on-farm strategies that build resilience and increase crop production, especially in RVB.

These findings imply that farmers in RVB are more likely than BVB to respond to biophysical risks, even though impacts on both basins are perceived as a maximum risk. Under SI goals, the present study argues that farmers in RVB may be more resilient to biophysical risks than BVB by adopting more efficient on-farm strategies, which could increase productivity. These assessments provide possible biophysical reasons for the productivity differences between BVB and RVB. However, farmers in both basins experience severe biophysical risks that threaten the cropping system and could undermine SI efforts to increase and sustain crop productivity. Farmers' demographic characteristics could compound the vulnerabilities of some social groups, like older women, while other social groups, including young men, are more resilient to respond to biophysical risks. Any SI policy or intervention must employ collaborative efforts from a multilevel perspective in participatory processes that engage all social groups to achieve SI goals with no one left behind within the cropping system. The next chapter examines the socioeconomic characteristics of productivity and livelihood outcomes that could enable or hinder SI goals in RVB and BVB.

CHAPTER 6

SOCIOECONOMIC CHARACTERISTICS OF CROPPING PRODUCTION SYSTEMS IN BVB AND RVB WITHIN SEMI-ARID NORTHERN GHANA, AND IMPLICATIONS FOR SI

6.1 Introduction

This PhD aims to determine the factors contributing to productivity differences between RVB and BVB and how these factors could influence the implementation of SI within smallholder agriculture systems in semi-arid Northern Ghana. The study's objectives are to assess and compare the biophysical, socioeconomic and institutional characteristics of the smallholder agriculture system that could hinder or enable SI in Northern Ghana. The chapter in objective 2 examines and compares the socioeconomic characteristics of the crop production system in RVB and BVB and discusses their implications for implementing SI in semi-arid Northern Ghana. The chapter answers these broader questions: *i)* What are the socioeconomic characteristics of semi-arid Northern Ghana that can hinder or enable crop productivity and economic outcomes in RVB and BVB? and *ii)* What implications will the identified socioeconomic characteristics have on achieving SI goals of productivity, resilience, efficiency and equity in RVB and BVB? Two types of data are used: primary data from household surveys, KIIs and FGDs, and secondary data from various sources that quantify some characteristics, including yield levels, cultivated area, and crop types.

The chapter covers the following sections: **5.2** presents results of farmers' land use (cropland sizes and crop types), yield outcomes (expected, actuals, consumed and sold yields/ha), economic characteristics (expenditure, yield incomes, off-farm incomes, household savings and loans) and available agriculture resources (participation in FBO and inputs/services) alongside available secondary data on these factors between basins; **5.3** analyses the associations between socioeconomic factors alongside household/demographic information (including community, age, gender and education) within and between basins; **5.4** discusses the findings alongside previous studies in Northern Ghana and their implications for SI principles (productivity, resilience, efficiency and equity); **5.5** looks at the practical application of SI in Northern Ghana and West Africa based on the findings; **5.6** summaries the chapter.

6.2 Results: Socioeconomic characteristics of smallholder farmers in the RVB and BVB

6.2.1 Crop type and land use

This sub-section explores and compares the different crop types and land use characteristics that could contribute to crop productivity in RVB and BVB.

6.2.1.1 Cultivated crops

The dominant crops in RVB and BVB include cereals like maize – *Zea mays*, millet – *Pennisetum glaucum*, sorghum – *Sorghum bicolor*, and rice - *Oryza sativa*, as well as legumes like groundnut - *Arachis hypogaea* and soya bean - *Glycine max*. Maize is profitable, widespread and considered a primary crop under the government's planting for Food and Jobs (PFJ) programme for household food needs in RVB and BVB (Abdallah et al., 2021; MOFA, 2017). Maize production is predominantly rainfed and cultivated on compound/garden farms with mostly certified open-pollinated varieties (OPV), hybrid, and local seeds. The certified varieties are subsidised and promoted through the PFJ programme, while local seeds are often uncertified varieties sourced from local farmers/growers in RVB and BVB. **Table 38** below describes the various certified maize varieties in RVB and BVB.

Other cereals (millet, sorghum, and rice) and legumes (groundnuts and soya beans) are cultivated on cropland further away from the homestead as secondary crops. Field observations reveal that the distant croplands are extensive and used for growing secondary crops, while compound croplands are smaller and used for cultivating primary crops. Pearson's chi-square results show that the pattern of crops grown as primary/maize crops is similar ($p > 0.05$), while secondary crops differ ($p < 0.001$) between RVB and BVB. **Table 39** below shows respondents who grow primary and secondary crops in RVB and BVB.

Nearly all respondents in both basins cultivate maize as a primary crop, while most secondary crops are legumes (groundnuts) in BVB and other cereals (millet [56%], sorghum [20%], and rice [15%]) are more predominant as secondary crops in the RVB.

Table 38*: Certified maize varieties promoted by extension services in RVB and BVB.* (Source: IFDC, 2016)

Variety	Type	Release dates	Description	Maturity days	Yield range (t/ha)	Certified by
Obaatanpa	OPV	1992	Common maize variety in Ghana. It has normal grains, dent texture and white colour	105 - 110	4 - 5	CSIR-SARI
Sanzal-Sima	OPV	2012	Drought and disease (Striga) tolerant. Normal grains and white colour	110	5 - 6	CSIR-SARI
Mamaba	Hybrid	1997	Locally developed, normal grains, flint and white colour	110	6 - 7	CSIR, CRI and CSIR-SARI
Sika-Aburoo (PAN53)	Hybrid	2015	Normal grain, white colour, flint/dent and large seed size	105 - 110	5 - 6	CSIR-SARI, CRI and Wienco
Bihilifa	OPV	2012	Normal grains, semi-flint, yellow colour and medium seed size	110	4 - 5	CSIR-SARI and CSIR-CRI
Ewul-Buyo	OPV	2012	Normal grain, white colour, flint/dent and medium seed size	90	5 – 6	CSIR-SARI and CSIR-CRI
Okomasa	OPV	1988	One of the earliest varieties in Ghana. Normal grain, white colour, dent and large seed size	120	5 - 6	CSIR-SARI and CSIR-CRI
Wang-Dataa	OPV	2012	Normal grain, white colour, flint and medium seed size	90	4 - 5	CSIR-SARI and CSIR-CRI

Open-pollinated varieties (OPV): *are a type of variety that comes from the multiplication by free-pollination of a set of individuals* | **Hybrid varieties:** *are the results of the fertilization of one maize plant by another genetically unrelated plant.* | **dent**: *contain hard and soft starch that becomes indented at maturity and either white or yellow.* | **flint:** *distinguished by a hard outer shell and kernels with a range of colours from white to red.*

Table 39: *Percentage of respondents who cultivate primary and secondary crops between RVB and BVB. (Source: Survey, 2020).*

Basin	Primary Crop	Secondary Crop				
	Maize	*Millet*	*Sorghum*	*Groundnut*	*Soya bean*	*Rice*
RVB	97%	55.8%	20.0%	7.9%	1.1%	15.3%
BVB	98%	1.5%	4.5%	92.4%	1.0%	0.5%

6.2.1.2 Cropland ownership and size under cultivation

Respondents utilise three types of croplands in RVB and BVB: *(i)* compound/garden croplands for primary crops and continuous cropping; *(ii)* distant croplands belonging to extended family and controlled by the family head; and *(iii)* community croplands, often scattered croplands in forest/shrub areas, belonging to the community and governed by the traditional authority. Compound/garden and distant croplands are mostly accessed through family affiliation (including marriage and inheritance), while community croplands could be rented or purchased by farmers who may require extra croplands or used by migrants without family lands. Pearson's Chi-square test shows that cropland acquisition patterns are similar ($p > 0.05$) between RVB and BVB. Over 80% of respondents in RVB and BVB acquire croplands through family affiliation, while less than 15% are rented or purchased, as shown in **Figure 17** below.

The household head controls the compound/garden cropland near the homestead, while the extended family head controls distant cropland further away. The extended family is a collection of households connected by lineage; as such, they may have common resources, including croplands. Household and extended family heads exert total control over croplands acquired through family affiliation (compound or distant) by determining their access and distribution among family members. For instance, in RVB and BVB, females cannot own family-affiliated croplands even though they may access them.

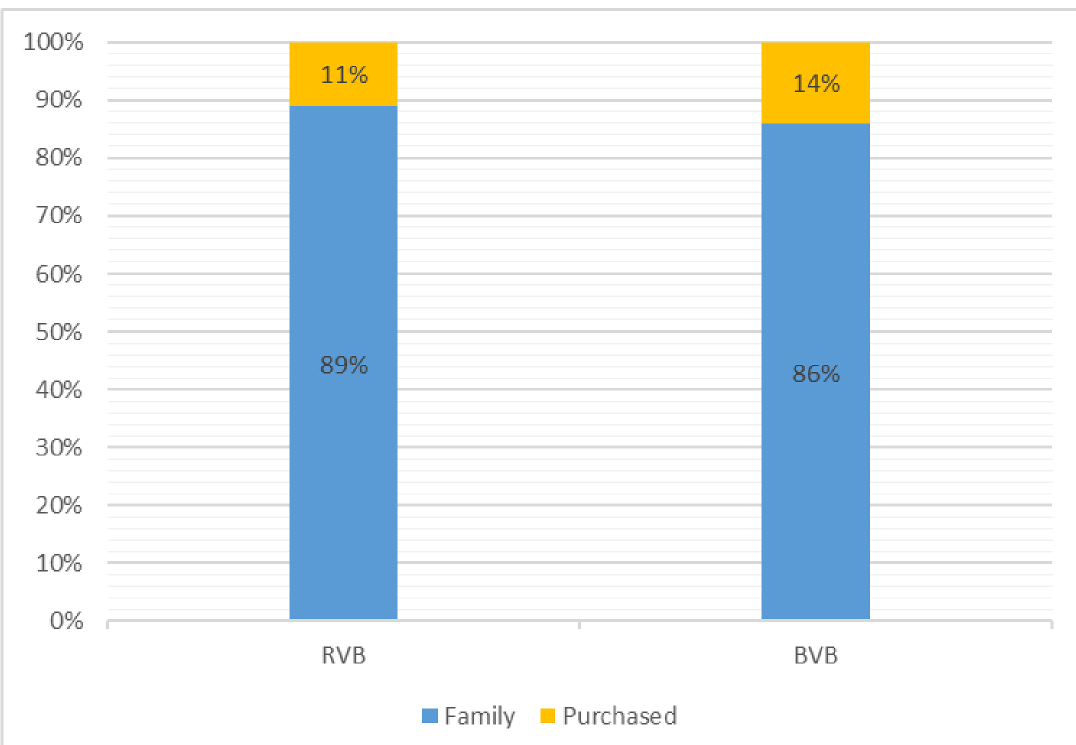

***Figure 17**: A Stacked chart comparing the percentages of how respondents access croplands between RVB and BVB.*

Mann-Whitney U test shows that the total cultivated farm sizes are similar ($p > 0.05$) between respondents in RVB and BVB. However, respondents in RVB have a higher farm size range, while those in BVB may have 0.2ha (average) more cropland than those in RVB, as shown in **Figure 18** and **Table 40** below.

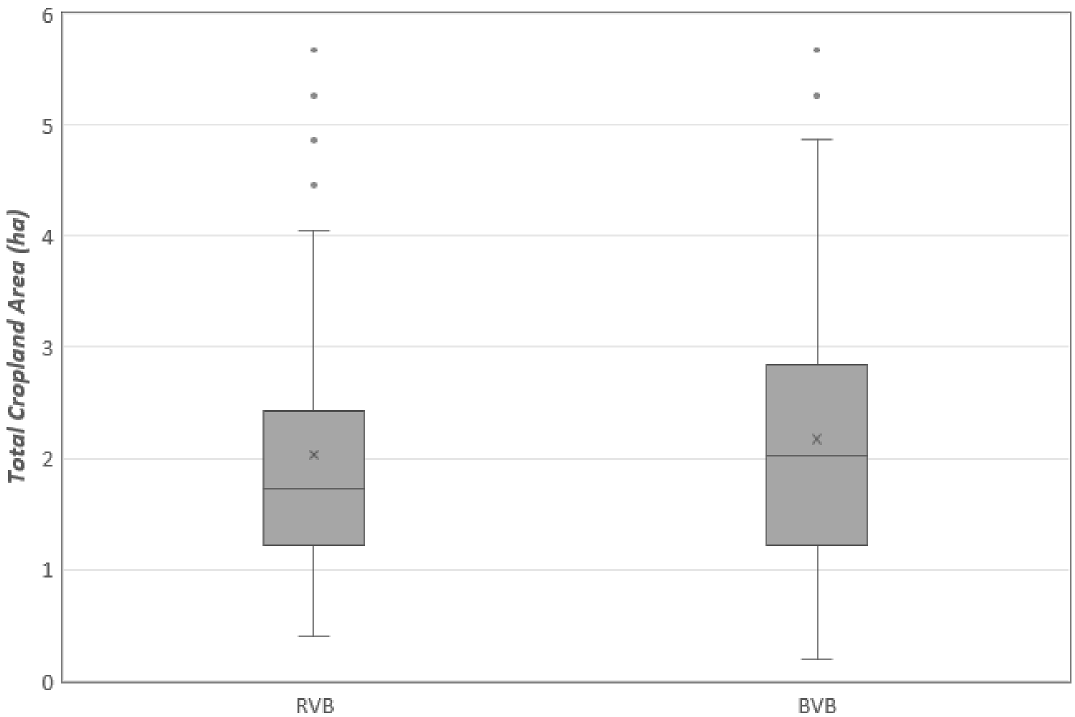

Figure 18: *Box and whisker plot comparing the total cropland between RVB and BVB (See* ***Appendix H(i)*** *for details of the plot).*

Table 40: *Comparing the median, mini, maxi, mean and standard deviation (SD) of cropland size between RVB and BVB.*

						Percentiles (ha)		
Basin	**N**	**Mean (ha)**	**SD (ha)**	**Mini (ha)**	**Max (ha)**	**25th**	**50th**	**75th**
RVB	200	2.0	1.3	0.41	7.7	1.2	1.7	2.4
BVB	200	2.2	1.3	0.2	6.9	1.2	2.0	2.8

6.2.1.3 Cropland for dominant crops

The Mann-Whitney U test shows that the cropland sizes allocated for the primary crop differ ($p = 0.04$) between respondents in RVB and BVB, while that of the secondary crops is similar ($p = 0.15$) between basins. However, the average cropland sizes allocated to the primary and secondary crops are higher in BVB than in RVB, as shown in **Figure 19** and **Table 41** below. The results further indicate that respondents in both basins allocate more cropland for maize production than other crops.

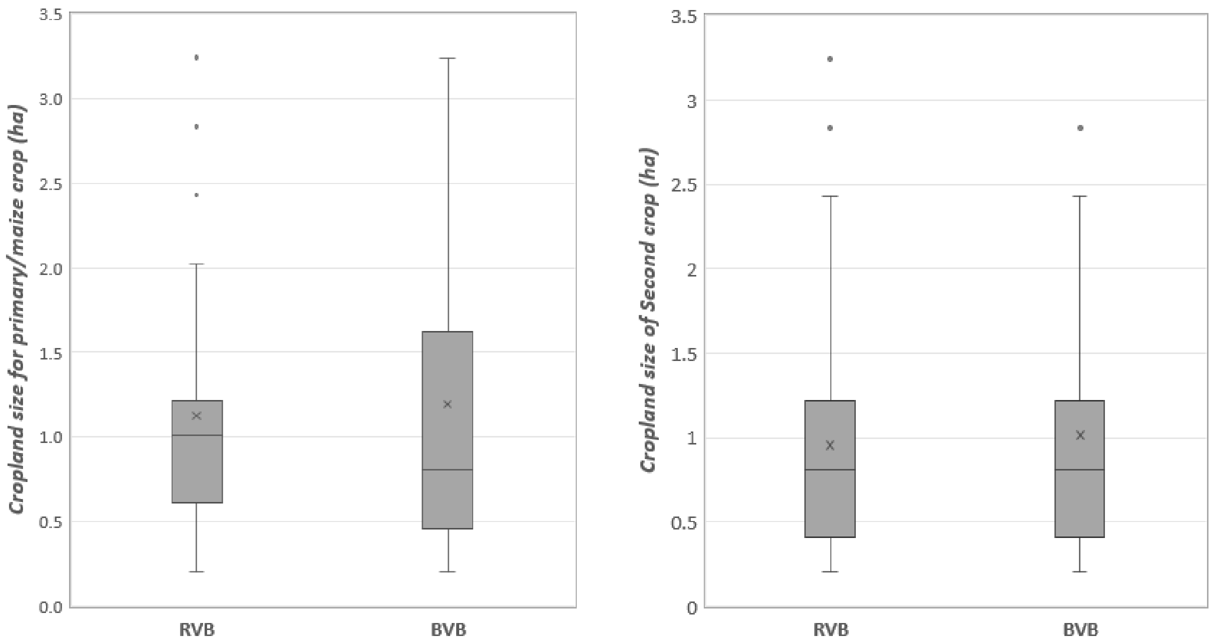

Figure 19: *Box and whisker plot comparing the total cropland under primary and secondary crops between RVB and BVB.*

Table 41: *The median, minimum, maximum, mean and standard deviation of cropland size under primary and secondary crops in RVB and BVB. (Source: Field Survey).*

							Percentiles		
Crops	**Basin**	**N**	**Mean**	**SD**	**Mini**	**Max**	**25th**	**50th**	**75th**
Primary crop (ha)	*RV*	200	1.1	.7	.2	4.5	.6	1	1.2
	BV	196	1.2	.8	.2	4.5	.5	.8	1.6
Secondary crop (ha)	*RV*	190	.9	.7	.2	4	.4	.8	1.2
	BV	198	1	.6	.2	4	.4	.8	1.2

Historically, cropland areas for primary and secondary crops have steadily increased. Cropland area allocated for primary (2007 to 2020) and secondary crop (2001 to 2020) production has been higher in BVB than in RVB, as shown in **Figure 18** below. However, the area allocated for secondary crop production (groundnut and millet) has been higher than the area for maize production, especially from 2001 to 2008 and 2012 to 2020. Even though landuse for primary and secondary crops was low for both basins in 2000/2001, 2008/2009, 2012/2013 and 2016/2017, increases were noticed in subsequent years. This observation could be due to national election periods where the sitting government invests less in agriculture and more in infrastructural projects (such as roads, schools and hospitals). No records were found for maize in RVB prior to 2007, possibly due to measurement issues and not zero production.

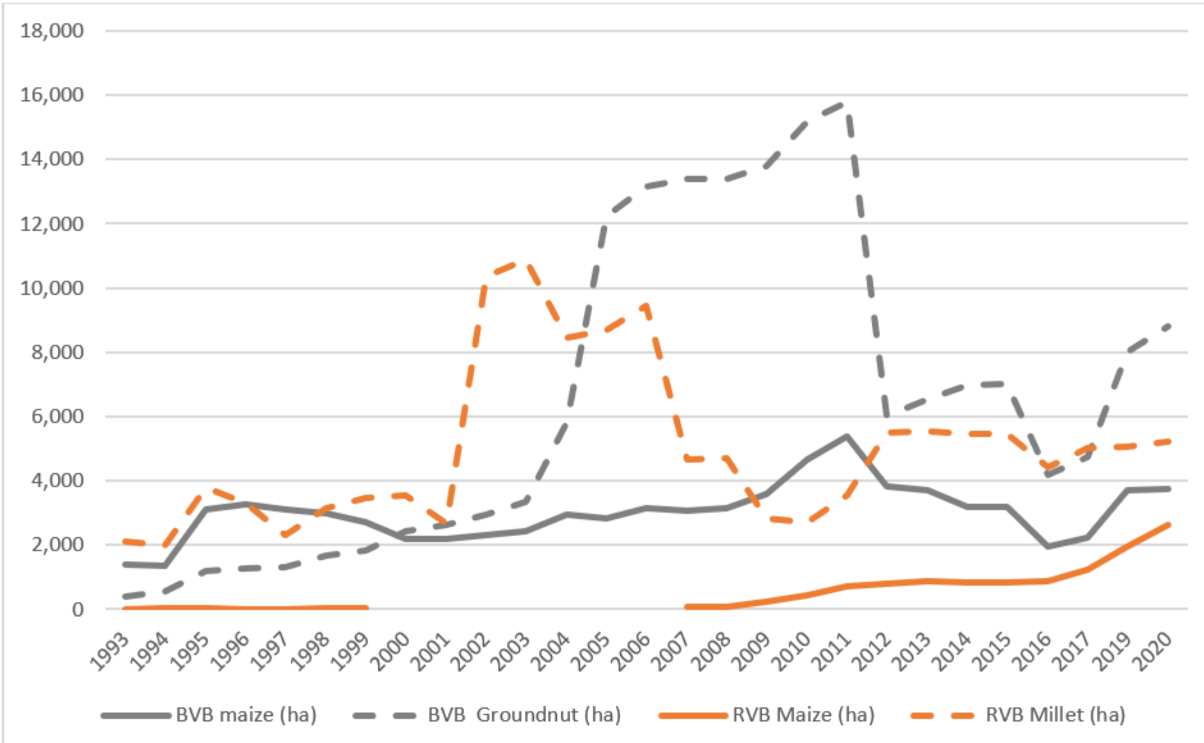

Figure 20: *Time series (1993 to 2020) comparing the total land area allocated for primary (maize) and secondary (millet and groundnut) crop production between RVB and BVB.* (Source: Bongo-DOA, 2020; Lawra-DOA, 2020; MoFA & GSS, 2019).

In summary, the results showed that maize is the most relevant household crop, while other cereals and legumes are supplementary crops for extra food or income for farmers in RVB and BVB. The expansion of maize is accelerated through onset of climate change to replace more traditional sorghum and millet, due to its short growing cycle, and it has also become a major staple in the diet for most households in Northern Ghana. However, respondents in RVB prefer growing different cereal crops (maize, millet, sorghum and rice), while those in BVB combine cereals (maize) and legumes (groundnut). The possible reason for the different crop types is explained in **section 6.2.3** below. The results further indicated that the average cropland size allocated for the primary crop is higher in BVB than RVB, while the cropland size under secondary crop production is similar. Most of the croplands in both basins are acquired through family affiliation and a few through direct purchase or rental in the form of shared cropping.

6.2.3 Crop production outcomes

This sub-section compares primary and secondary crop production outcomes (mt/ha), including expected yields, actual yields, consumed yields, sold yields, and others in RVB and BVB.

6.2.3.1 Expected and actual crop production outcomes

Expected yield outcomes are respondents' harvest expectations, considering the resources (land, inputs/service and labour) they have committed towards farming. Actual yield outcomes indicate crop production levels under biophysical and socioeconomic conditions for the farming season.

For the primary crop, the Mann-Whitney U tests show that respondents' expected yield/ha ($p < 0.001$) and actual yield/ha ($p < 0.001$) are higher in RVB than BVB, as shown in **Table 42** and **Figure 21** below. However, the SD shows a wider range of individual expected and actual yield/ha estimates in BVB than in RVB. The results suggest that respondents in RVB are more likely to have higher expectations and produce more primary/maize crops than those in BVB.

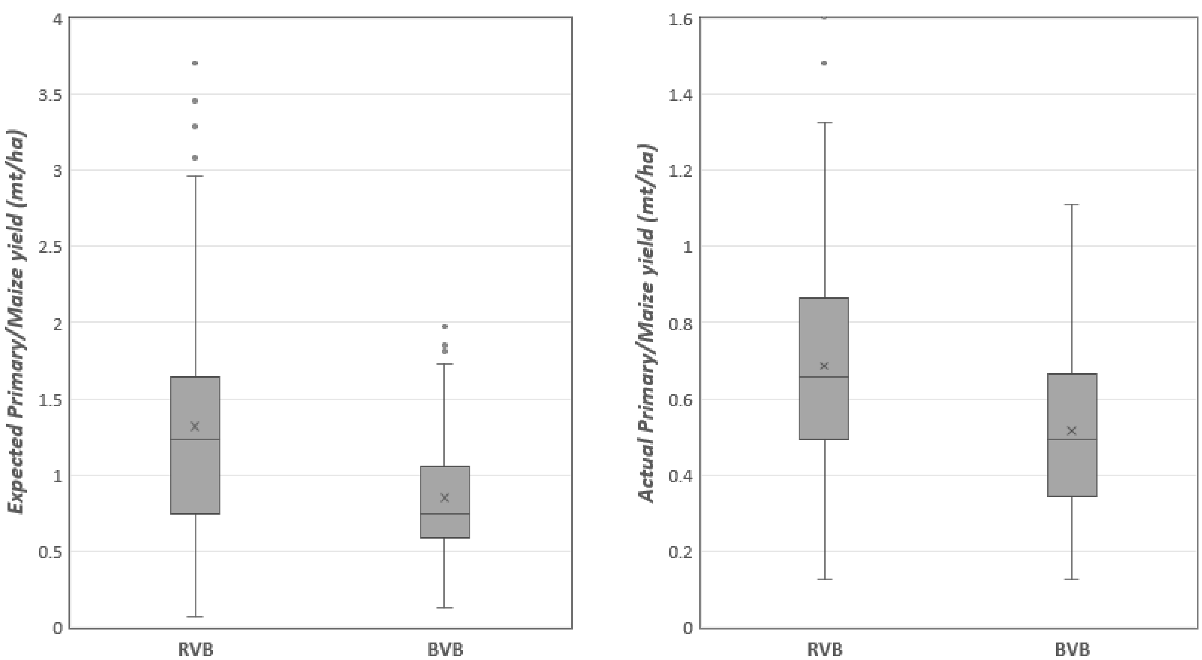

Figure 21: *Box and whisker plot comparing expected and actual primary/maize yields (mt/ha) between RVB and BVB.*

For secondary crops, the Mann-Whitney U tests show that respondents' total expected yield/ha ($p = 0.05$) and actual yield/ha ($p < 0.001$) differ between RVB and BVB, as shown in **Table 42** and **Figure 22** below. For instance, respondents' average expected, and actual groundnut yield/ha are higher in BVB than in RVB. However, the yield/ha of actual and expected cereals (millet, sorghum and rice) are higher in RVB than in BVB. The results suggest that respondents in BVB are more likely to produce more groundnuts as cash crops than those in RVB, who may produce more cereals as household food crops.

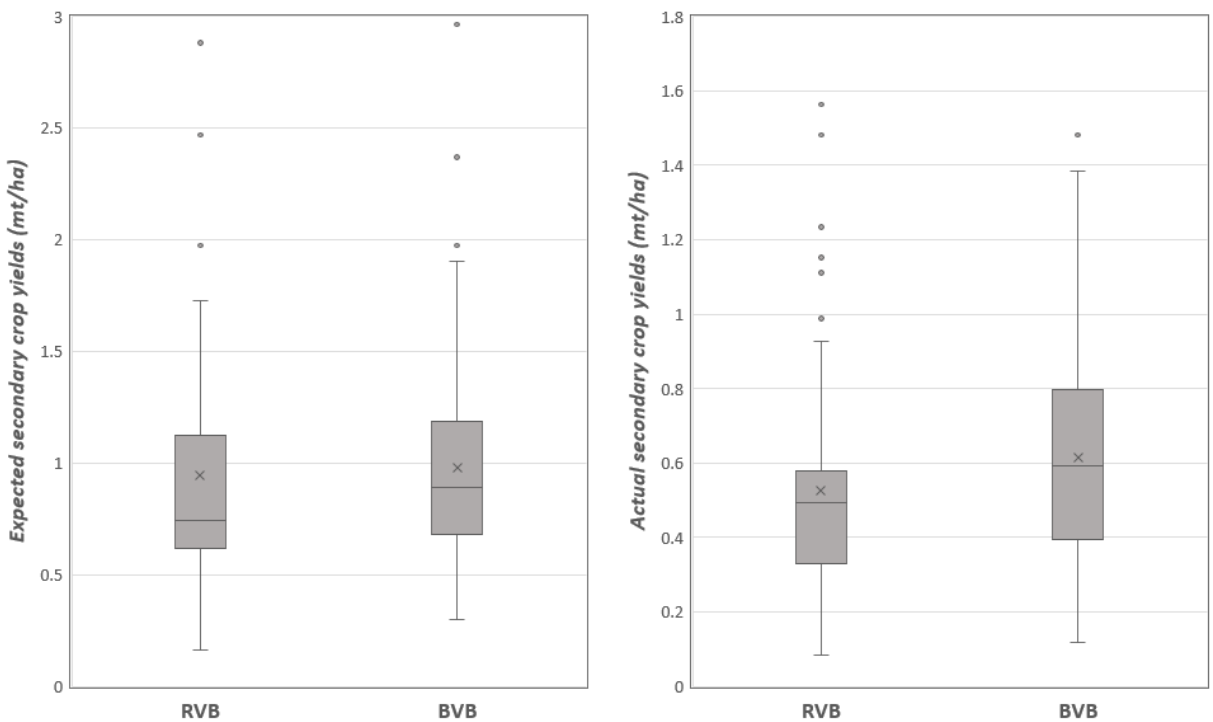

Figure 22: *Box and whisker plot comparing the overall expected and actual secondary crop yields (mt/ha) between RVB and BVB.*

Generally, the primary crops' yield/ha expectations were not met in both basins, even though respondents in RVB *(-47%)* are slightly less likely to meet potential yields than those in BVB *(-38%)*. Similarly, the actual yield/ha did not meet potential yields for all secondary crops in RVB *(millet [-28%], sorghum [-33%], groundnut [-27%], soya bean [-30%] and rice [-27%])* and BVB *(millet [-31%], sorghum [-40%], groundnut [-22%], soya bean [-29%] and rice [-29%])* by an average of *30%.*

Even though respondents did not meet their yield/ha expectations, simple linear regression analysis shows strong evidence that primary/maize yield/ha expectations can predict actual yield/ha in RVB ($r = 0.6$, $p < 0.001$) and BVB ($r = 0.7$, $p < 0.001$). Also, secondary crops' yield/ha expectations can predict actual yield/ha in RVB ($r = 0.8$, $p < 0.001$) and BVB ($r = 0.8$, $p < 0.001$). This evidence suggests that respondents who expect more yields are likely to receive higher actual yields than those who expect fewer in both basins.

Table 42: *Comparing the expected and actual yield/ha for primary and secondary crops' (millet, sorghum, groundnut, soya bean and rice) between RVB and BVB. (Source: Field survey, 2020)*

					Mt/ha		Range mt/ha		Percentiles (mt/ha)		
Category	**Crop type**	**Yield/ha**	**Basin**	**N**	**Mean**	**SD**	**Mini**	**Max**	**25th**	**50th**	**75th**
Primary Crop	Maize	Expected	*RV*	200	1.31	.71	.07	3.70	.74	1.23	1.65
			BV	200	.83	.35	.00	1.98	.58	.74	1.06
		Actual	*RV*	200	.69	.32	.12	1.70	.49	.66	.86
			BV	200	.51	.25	.00	1.73	.33	.49	.65
Secondary crop	Millet	Expected	*RV*	106	.83	.50	.16	4.94	.62	.74	.99
			BV	3	.59	.51	.30	1.19	.30	.30	1.19
		Actual	*RV*	106	.47	.20	.08	1.48	.37	.49	.56
			BV	3	.31	.12	.20	.44	.20	.30	.44
	Sorghum	Expected	*RV*	38	.78	.32	.37	1.98	.62	.74	.82
			BV	9	.91	.37	.44	1.48	.59	.89	1.19
		Actual	*RV*	38	.39	.19	.12	1.11	.25	.37	.49
			BV	9	.39	.20	.15	.74	.30	.40	.44
	Groundnut	Expected	*RV*	15	.98	.50	.41	2.47	.74	.99	1.23
			BV	183	.99	.42	.40	2.96	.74	.89	1.19
		Actual	*RV*	15	.56	.28	.25	1.23	.37	.49	.74
			BV	183	.63	.31	.12	2.07	.44	.59	.89
	Soya Bean	Expected	*RV*	2	.46	.22	.31	.62	.31	.46	.62
			BV	2	.67	.10	.59	.74	.59	.67	.74
		Actual	*RV*	2	.25	.00	.25	.25	.25	.25	.25
			BV	2	.37	.10	.30	.44	.30	.37	.44
	Rice	Expected	*RV*	29	1.56	.52	.64	2.88	1.23	1.48	1.73
			BV	1	1.48	.	1.48	1.48	1.48	1.48	1.48
		Actual	*RV*	29	.90	.48	.25	2.47	.49	.86	1.23
			BV	1	.81	.	.81	.81	.81	.81	.81

Historically, yield trends (1993 – 2020) for maize and second crops (legumes and cereals) in the RVB and BVB have been significantly different. Similar to the results from the survey, maize yields in RVB have been significantly higher for most periods than the yield levels in BVB, as shown in **Figure 23** below. These average yields from secondary data for the past 10 years (2010 – 2020) are higher than the respondents' expected yield/ha reported in the survey. The possible reason for the differences could be the survey's smaller sample size or the problem of DOA officials reporting a more favourable productivity outcome in operational areas for career promotion. However, the sudden jump in crop yields from 2017 to 2020 could be due to the government PFJ programme implemented by the government of Ghana to boost agriculture with subsidized inputs and extension services.

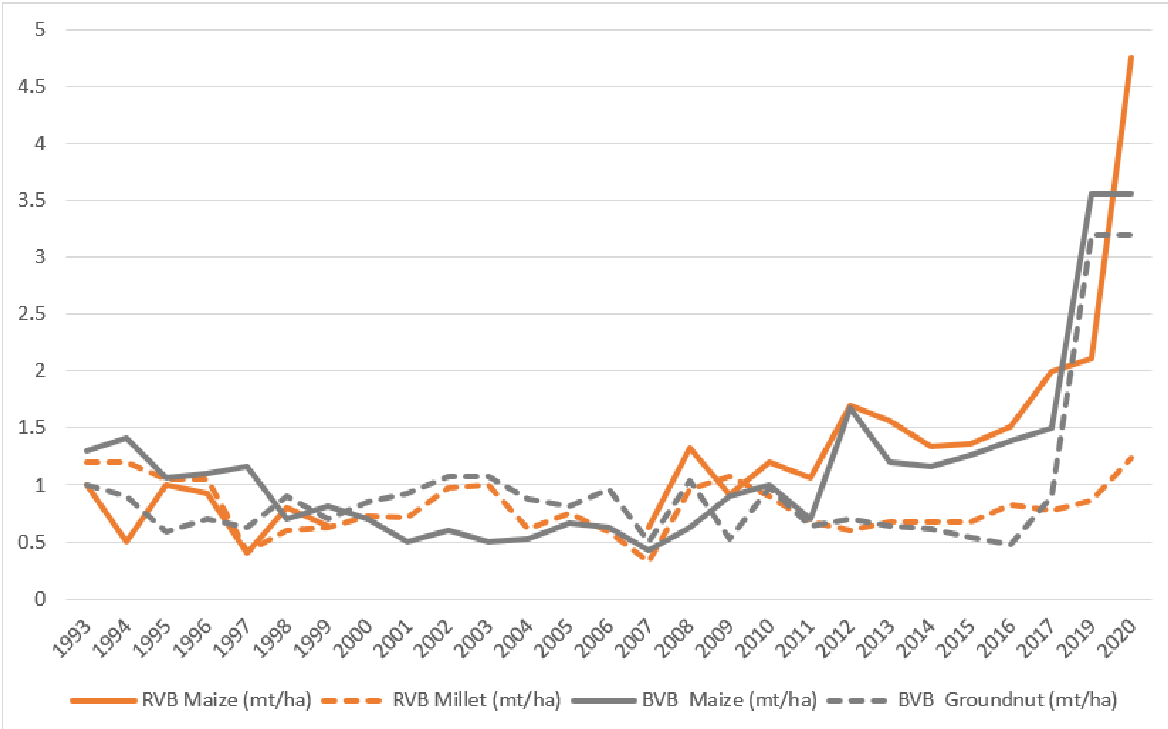

Figure 23: *Comparing yield/ha trend for primary (Maize) and secondary crops (groundnut and millet) between RVB and BVB.* (Source: Bongo-DOA, 2020; Lawra-DOA, 2020; MoFA & GSS, 2019).

6.2.3.2 Crop yields consumed, sold and for other purposes

Primary and secondary crops are produced for household consumption, the market and other social purposes (ceremonies). Crop usage characteristics may be crucial for crop production patterns between RVB and BVB.

For the primary crop, the Mann-Whitney U test shows that the pattern of primary crop yield/ha consumed ($p < 0.001$) and for other purposes ($p < 0.001$) differ, while yield/ha sold ($p > 0.05$) are similar between respondents in RVB and BVB. As shown in **Figure 24** and **Table 43** below, the household's average amounts of the primary crop consumed and for other purposes are higher in RVB than BVB, while the average sold is similar between both basins. About 72% of actual maize yield in RVB is for household consumption, 21% for sale and 7% for other purposes. On the contrary, 68% of actual maize yield is produced for household consumption, while 27% is for sale and 5% for other purposes. Maize is a household food crop with a higher consumption pattern than sales in both RVB and BVB. The most popular staple foods in both basins are made from maize, including "Tuozafi", "Banku", and "Koko".

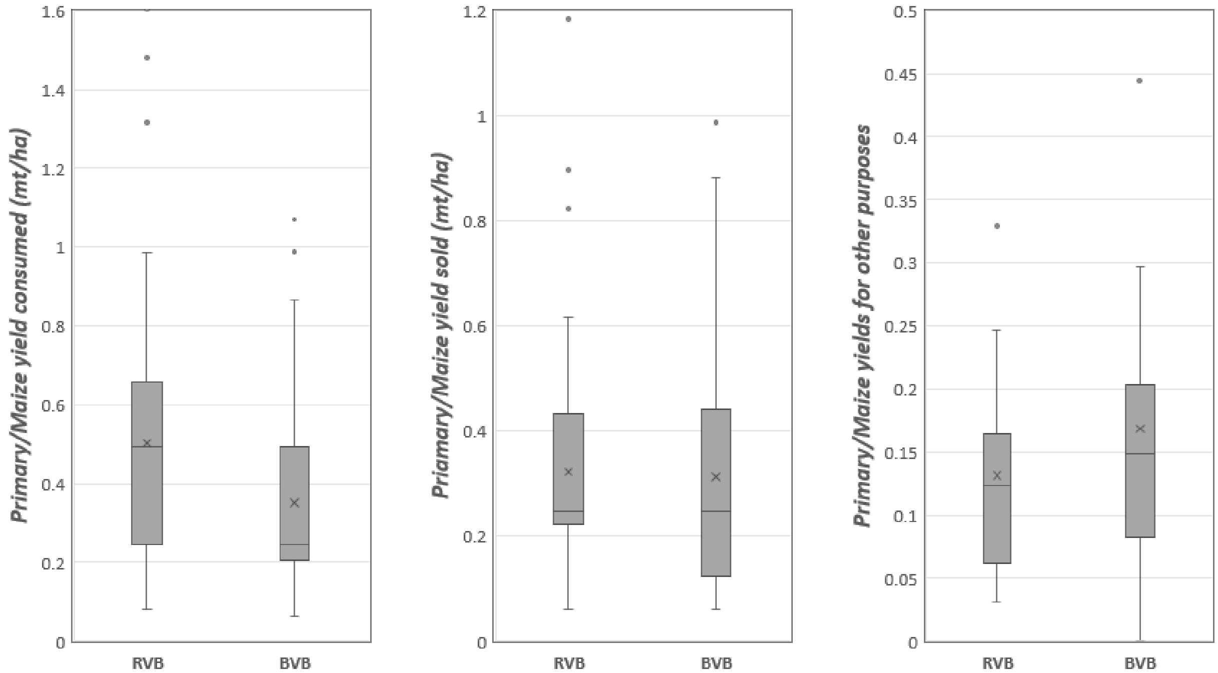

Figure 24: *Box and whisker plot comparing primary yield (mt/ha) consumed, sold and for other purposes between RVB and BVB.*

For the secondary crops, the Mann-Whitney U test indicated that the pattern of total crop yield/ha consumed ($p < 0.001$) and sold ($p < 0.001$) are not the same between RVB and BVB. As shown in **Figure 25** and **Table 43** below, the average amount of secondary crops consumed is higher in RVB than in BVB, while the average amount sold is higher in BVB than in RVB. About 77% of actual secondary yields are for household consumption, 22% for sale and 1% for other purposes. On the contrary, 34% of actual yield/ha is produced for household consumption, while 55% is for sale and 11% for other purposes. Overall, more crop yields (primary and secondary) are consumed in RVB than in BVB, while more are sold in BVB than in RVB.

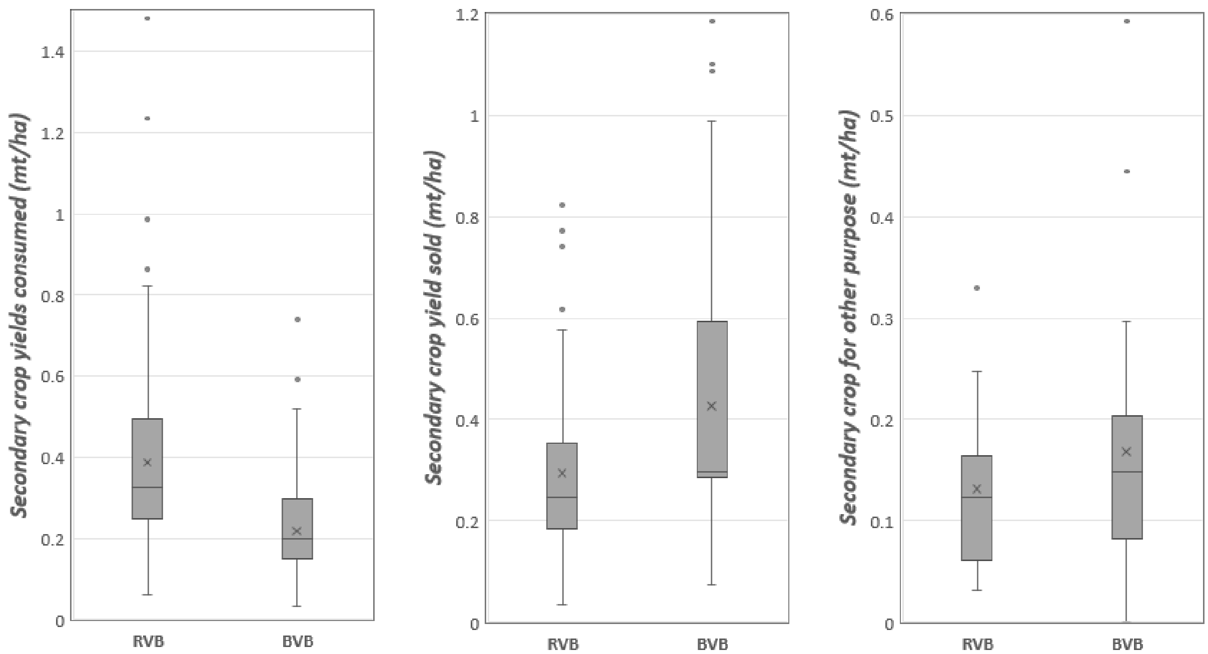

Figure 25: *Box and whisker plot comparing secondary crop yield (mt/ha) consumed, sold and for other purposes between RVB and BVB.*

These results suggest a pattern of subsistence agriculture practice in RVB and a more commercial system in BVB. The possible reason for the higher consumption of primary and secondary crops in RVB than in BVB could be the differences in consumption per capita (mt/capita) ($p < 0.001$) and population density. From the survey, the average consumption in RVB (4.7 mt/capita) is more than that of BVB (3.3 mt/capita). However, the low population density in BVB (114 persons/km^2) implies that households could afford to diversify food crops with cash crops more than in RVB (283 persons/km^2).

Simple linear regression shows that the overall actual yield/ha could predict the overall yield/ha consumed in RVB ($r = 0.66$, $p < 0.001$) and BVB ($r = 0.38$, $p < 0.001$). Also, the overall actual yield/ha could predict the overall yield/ha sold in RVB ($r = 0.59$, $p < 0.001$) and BVB ($r = 0.73$, $p < 0.001$). These results suggest that respondents with higher yields could also increase their household food consumption and have extra for the market.

Table 43: *Primary and Secondary crops sold, consumed and for other purposes between RVB and BVB. (Source: Field Survey).*

		mt/ha				mt/ha		Percentiles (mt/ha)		
Crop type	**Category**	**Basin**	**N**	**Mean**	**SD**	**Mini**	**Max**	**25th**	**50th**	**75th**
Primary crop (Maize)	Consumed (mt/ha)	*RV*	200	.50	.34	.08	2.96	.25	.49	.66
		BV	200	.34	.21	.00	1.07	.16	.25	.49
	Sold (mt/ha)	*RV*	196	.15	.21	.00	1.19	.00	.00	.25
		BV	199	.14	.22	.00	.99	.00	.00	.25
	Other purpose (mt/ha)	*RV*	131	.08	.12	.00	.49	.00	.04	.12
		BV	200	.34	.21	.00	1.07	.19	.25	.49
Secondary Crop	Consumed (mt/ha)	*RV*	190	.40	.35	.00	2.47	.25	.31	.49
		BV	198	.21	.13	.00	.74	.12	.16	.30
	Sold (mt/ha)	*RV*	179	.12	.18	.00	.82	.00	.00	.25
		BV	200	.34	.21	.00	1.07	.16	.25	.49
	Other purpose (mt/ha)	*RV*	121	.07	.09	.00	.49	.00	.00	.12
		BV	198	.06	.11	.00	.89	.00	.00	.10

In summary, even though farmers in RVB and BVB may have higher yield expectations, the actual yield produced is about 40% less than expected in both basins. However, respondents in RVB are more likely than BVB to have more expected and actual yields for the primary crops (maize). On the other hand, respondents in BVB are more likely to cultivate more groundnut yields, while those in RVB are more likely to cultivate cereals yields/ha (millet, sorghum and rice) as secondary crops. Moreover, respondents in RVB consume more cereals as primary and secondary crops, while those in BVB sell more groundnuts as secondary crops.

6.2.4 Economic characteristics and outcomes

This sub-section compares farm expenditure and incomes, off-farm incomes (alternative livelihood income and remittances), savings and loans over the previous farming season between RVB and BVB.

6.2.4.1 Expenditure and incomes from crop yields

Respondents spend the most money on farm inputs and services to increase yields. Common inputs purchases include fertilizers, seeds, farm tools (hoes, cutlasses) and pesticides, while tractors and labour are the common services used. Subsistence farming incomes come from excess yields after meeting household food needs, while commercial farmers cultivate to meet market demand. The difference between expenditure and income determines yield profitability in RVB and BVB. See **Figure 26** and **Table 44** below.

Mann-Whitney U tests show that expenditure (p = 0.2) and incomes (p = 0.5) are similar between RVB and BVB, while profit/losses ($p < 0.001$) differ. The average amount spent as farm expenditure and received as yield incomes are almost the same across basins, while more losses are made in BVB than in RVB. However, the range and median farm expenditures and yield incomes are higher in RVB than in BVB.

Furthermore, respondents in BVB (93%) are more likely to sell more of their yields than those in RVB (54%). These results suggest that the production system practised (subsistence or commercial) in RVB and BVB may not differentiate respondents' farm expenditure or yield incomes. However, market failures, including price fluctuations, may impact a more commercially oriented agriculture system.

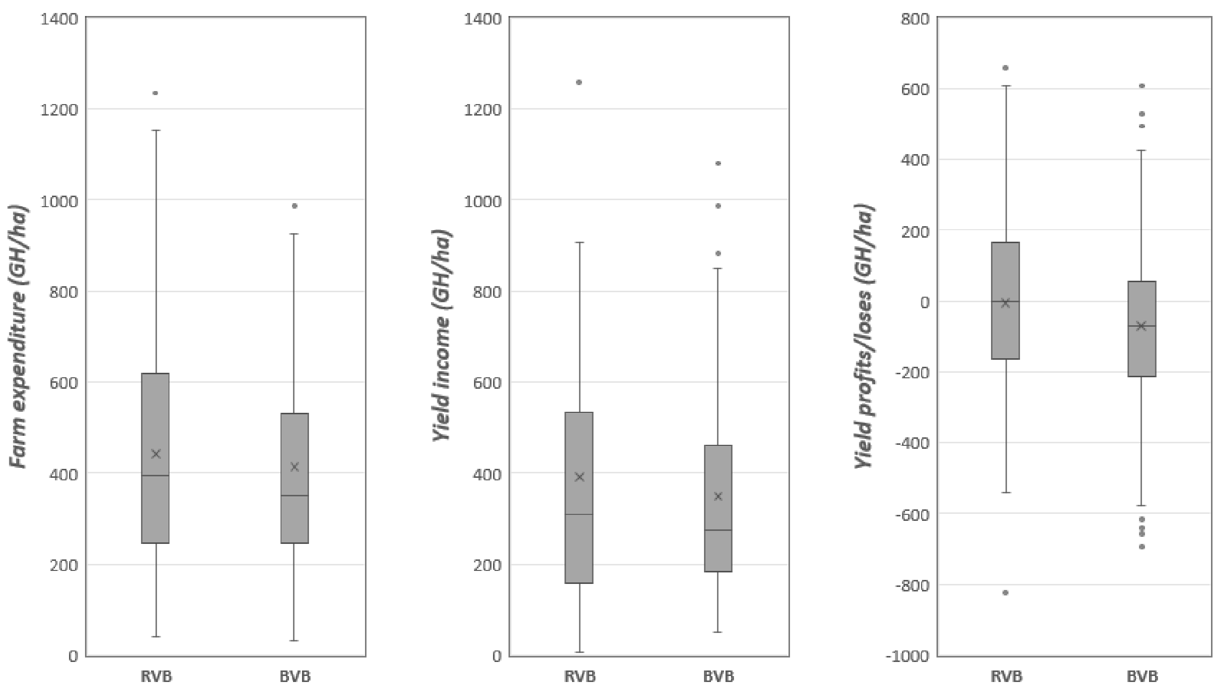

Figure 26*: Box and whisker plot comparing farm expenditure, yield incomes and profits/losses between RVB and BVB.*

***Table 44**: Farm expenditure, yield incomes, and profitability between RVB and BVB. (Source: Field Survey, 2020).*

							Percentiles		
Category	Basin	N	Mean	SD	Mini	Max	25th	50th	75th
Expenditure (GH/ha)	*RV*	199	442	262	41	1235	247	395	617
	BV	200	413	232	31	988	247	351	529
Incomes (GH/ha)	*RV*	107	391	271	6	1259	157	309	535
	BV	185	349	236	49	1080	182	274	461
Profit/Loss (GH/ha)	*RV*	107	-6	262	-823	658	-165	.00	164
	BV	185	-71	227	-692	608	-211	-70	56

These results suggest that farm expenditures are higher than incomes as other income sources, including alternative livelihood incomes, remittances, savings and loans, may be required to sustain crop production.

6.2.4.3 Off-farm incomes

Off-farm incomes include estimated annual incomes from alternative livelihood activities (such as petty/informal trading, food processing, labour and weaving) and remittances from migration. See **Figure 27** and **Table 45** below.

Mann-Whitney U tests show that the amount received as alternative livelihoods incomes ($p = 0.008$) and remittances ($p = 0.016$) differ between RVB and BVB.

Respondents in RVB (70%) tend to have higher average incomes from alternative livelihood activities than those in BVB (44%). However, the median income is similar between both basins. Moreover, respondents in RVB (31%) are more likely to receive higher remittances as off-farm income than those in BVB (25%). However, the average amount received as remittances is higher in BVB than in RVB. The number of households engaging in off-farm activities is discussed in **section 6.2.5** below.

These results suggest that respondents in RVB are more likely to rely on alternative livelihood activities, while those in BVB rely more on remittances for extra income besides farming. The results further suggest that off-farm activities provide farmers with more income than farming in the RVB and BVB. See **Figure 26** above.

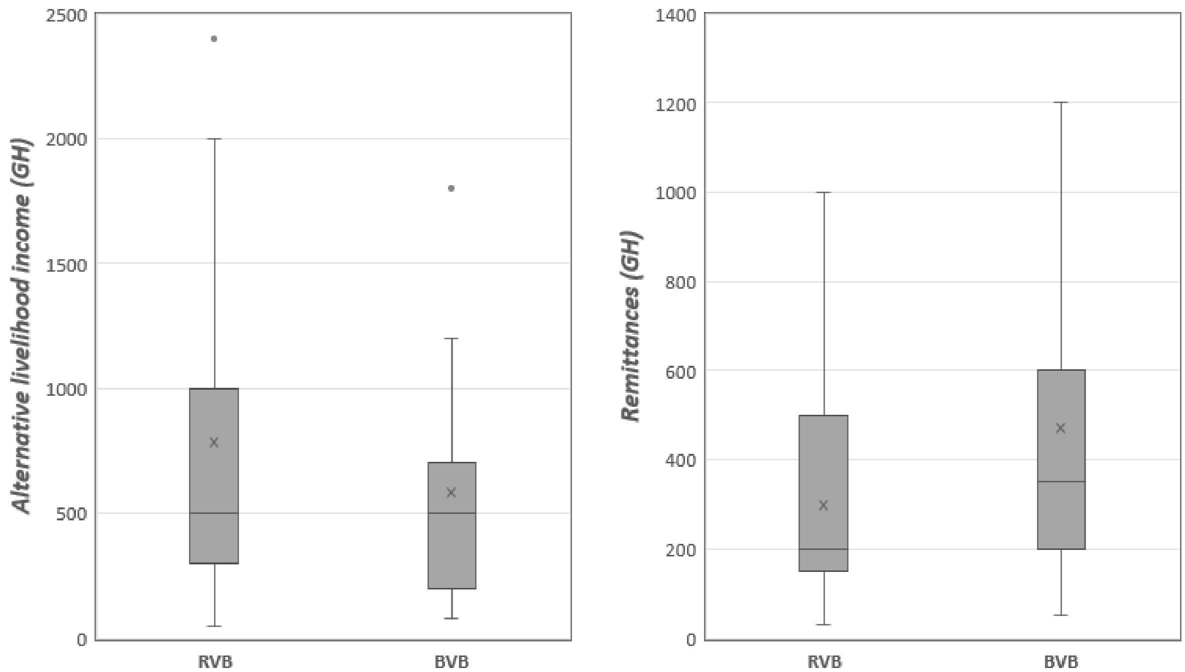

Figure 27: *Box and whisker plot comparing alternative livelihood income and remittances between RVB and BVB.*

Table 45*: Comparing the estimated annual alternative livelihood incomes and remittances between RVB and BVB.*

							Percentiles		
Category	**Basin**	**N**	**Mean**	**SD**	**Mini**	**Max**	**25th**	**50th**	**75th**
Alternative livelihood Income (GH)	*RV*	138	785	646	50	2400	300	500	1000
	BV	88	583	492	80	1800	200	500	700
Remittances (GH)	*RV*	62	297	197	30	1000	150	200	500
	BV	50	471	380	50	1500	200	350	600

Source: Survey, 2020

6.2.4.4 Savings and Loans

The most prominent savings and loan schemes in RVB and BVB are VSLAs, self-organised financial schemes that enable farmers to save and receive small loans. Some rural banks offer small loans to well-organized FBOs or farmers with collateral (house/vehicle), while others receive loans from market mediators who receive yields as repayment. This analysis defines savings and loans as the amount received from the previous year for current farming.

Parsons's chi-square tests show that the number of respondents with savings statistically differs ($p < 0.001$), while those who receive loans remain the same ($p > 0.05$) between basins. Respondents in RVB (53%) are more likely to have personal savings than those in BVB (36%). However, less than a quarter of respondents in RVB (21%) and BVB (17%) receive loans for farming.

Furthermore, Mann-Whitney U test shows that the amount of savings ($p < 0.001$) and loans received ($p < 0.001$) differ between basins. The average amount saved and borrowed are higher in BVB than in RVB, as shown in **Figure 28** and **Table 46** below. These results show that even though more respondents save and receive loans in RVB than in BVB, the amount saved and received as loans are higher in BVB than in RVB.

Moreover, Spearman's correlation shows a positive relationship between savings and loans in BVB ($r = 0.457$, $p = 0.028$) but not in RVB ($r = 0.067$, $p = 0.755$). This relationship suggests that savings increases with loans accessed in BVB, similar to the VSLA model operated at the community level, where savings determines the loan amount farmers can access.

These results could be due to the more commercial nature of the agriculture system in BVB, which facilitates opportunities like VSLAs that provides the means of accessing funds for farming.

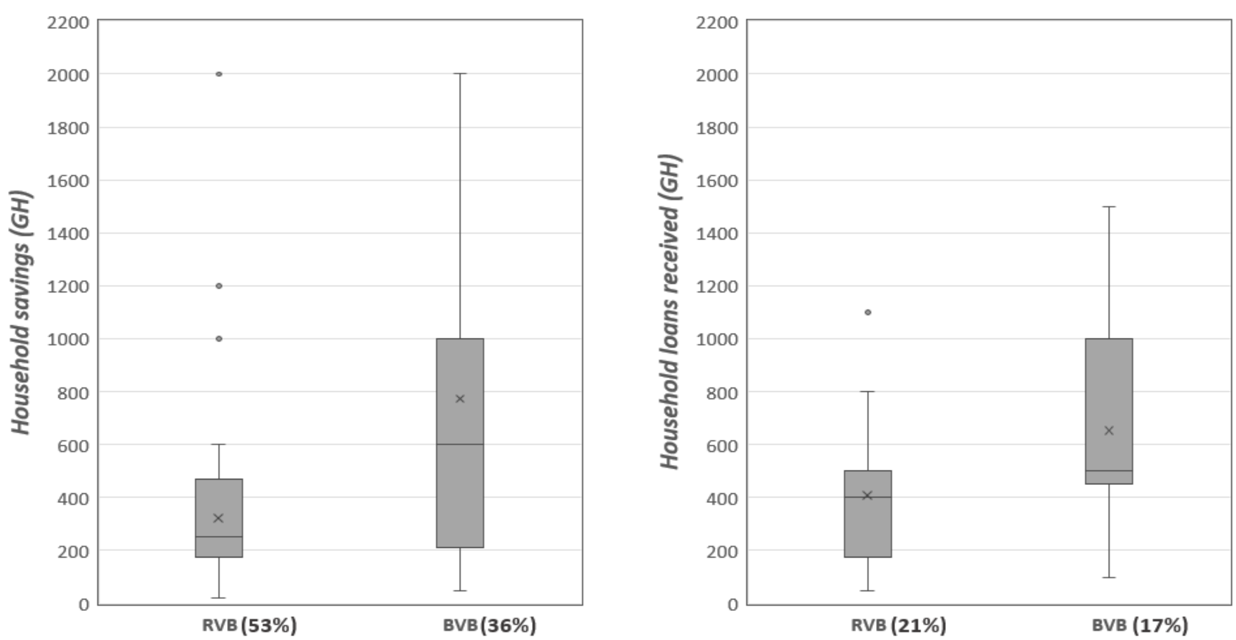

Figure 28: *Box and whisker plot comparing household savings and loans received between RVB and BVB.*

__Table 46__: Annual savings and loans received by smallholder farmers in the RVB and BVB. (Source: Field Survey, 2020).

							Percentiles		
Category	**Basin**	**N**	**Mean**	**SD**	**Mini**	**Max**	**25th**	**50th**	**75th**
Household savings	*RV*	105	321	268	20	2000	175	250	470
	BV	72	774	718	50	4500	213	600	1000
Household loans	*RV*	33	408	267	50	1100	175	400	500
	BV	41	652	351	100	1500	450	500	1000

In summary, economic characteristics such as farm expenditure and incomes are similar across RVB and BVB, while losses are higher in BVB than in RVB. Respondents in RVB rely more on alternative livelihood incomes, while those in BVB rely more on remittances as off-farm incomes. Savings and loans are not widespread in both basins, even though respondents in BVB are more likely to access loans than those in RVB.

6.2.5 Social and livelihood Characteristics

Social characteristics affecting crop yields/ha include alternative livelihood activities (number and types), participation in FBOs, migration patterns and access to agriculture inputs and services.

6.2.5.1 Off-farm activities

As noted earlier, alternative livelihood incomes and remittances from migration are the main off-farm income-generating activities in RVB and BVB. The alternative livelihood activities include petty trading (food, livestock, medication, agrochemicals and transportation), food processing (local beer brewing and shea butter processing), handicrafts (weaving of textiles, buckets and hats) and labour (formal and non-farm employment).

Pearson's chi-square test shows that the pattern of participation in alternative livelihood activities ($p < 0.001$) differs between respondents in RVB and BVB. From **Figure 29** below, respondents in BVB are more likely to engage in petty trading and labour than those in RVB, while those in RVB tend to engage in handicraft and food processing than those in BVB. The UER of Ghana is famous for weaving, especially hats, bags and buckets from straw and may indicate the reason for handicrafts in RVB. The demand for services and labour may be higher in BVB due to the more commercial farming activities and the youth population, who are more likely to participate in commercial agriculture. An AEA explained that young people from communities without irrigation opportunities in BVB travel to other communities along the river to provide labour and other services during the dry season.

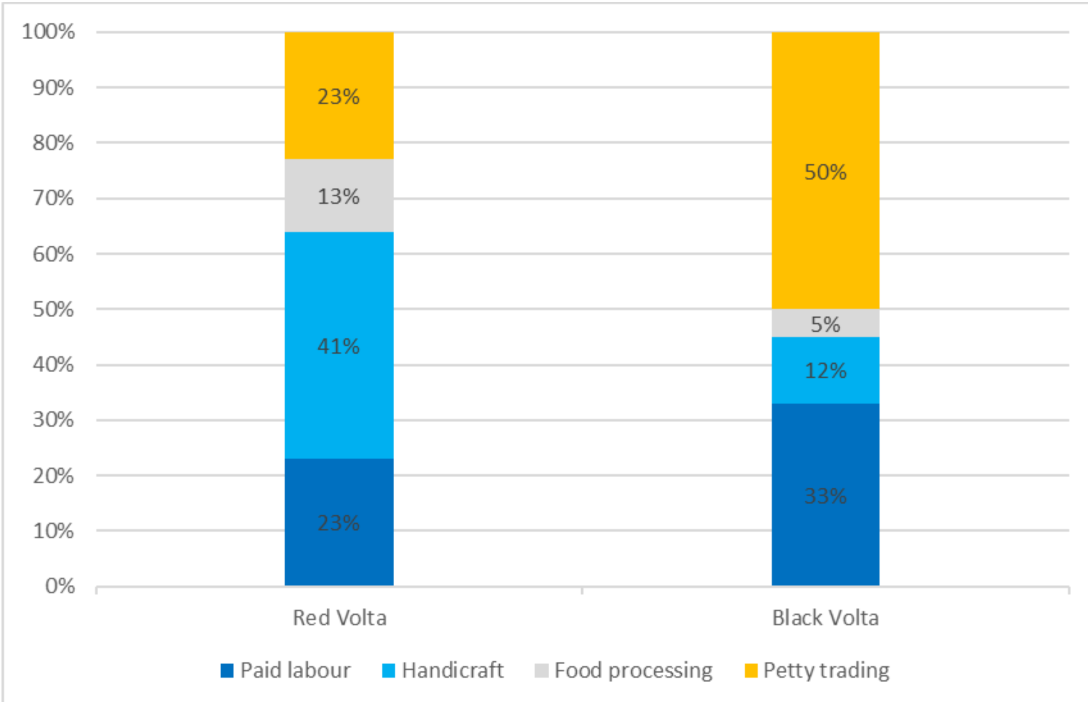

Figure 29*: A 100% stacked bar chart comparing the respondents participating in various alternative livelihood activities between RVB and BVB. (Source: Field survey, 2020).*

During the dry season, farmers without water sources for dry season farming travel to other parts of the country (mainly cities and farming communities in the South) and sometimes neighbouring countries (Burkina Faso and Togo) to find seasonal work.

Pearson's chi-square test shows migration frequency differs ($p < 0.001$) between respondents in RVB and BVB. From **Figure 30** below, respondents in BVB are more likely to have never migrated than those in RVB, while those who do not migrate frequently are more likely to be in RVB than in BVB. However, respondents in RVB are more likely to migrate "frequently" or "very frequently" than BVB.

Also, Pearson's Chi-square results ($p < 0.001$) suggest that migration is a more active off-farm activity in BVB (52%) than in RVB (41%), while alternative livelihood activity ($p < 0.001$) is a more active off-farm activity in RVB (77%) than BVB (59%). Moreover, respondents in BVB (54%) are more likely than those in RVB (36%) to consider migration as very beneficial ($p = 0.004$) for farming.

Most farmers who go on seasonal or sometimes permanent migration bring financial and other resources to improve their farming activities, especially those who produce cash crops. An FBO leader admitted to frequently participating in seasonal migration, an essential resource mobilization activity for farming.

"I often travel to Techiman to work as a labourer on farms during the dry season when we cannot farm due to the lack of irrigation farming in this community. Usually, I come back before the rainy season begins to prepare my land. Also, I make it a point to purchase the chemicals and tools needed for the farming season since they are expensive and often hard to find in this community".

- *FBO Leader, Zambo Community, BVB*

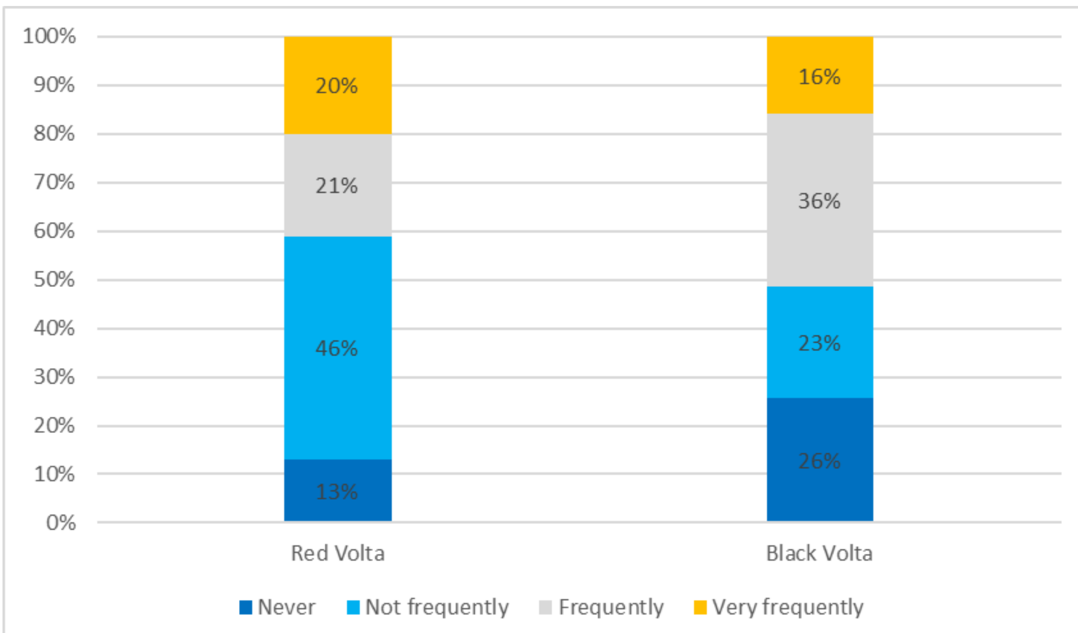

Figure 30*: 100% stacked bar chart comparing the migration frequency between RVB and BVB. Source: Field survey, 2020. (Source: Field Survey, 2020)*

6.2.5.2 FBO participation

Due to the low AEA to farmer ratio, FBOs in RVB and BVB are mostly informal self-organised groups at the local level supported by local institutions (DOA and NGOs) with extension services.

Generally, FBO participation in both basins is low even though respondents in RVB are more likely than those in BVB to belong to an FBO, as seen in **Figure 31** below. Pearson's chi-square test shows that participation in FBO activities differs ($p = 0.01$) between basins. Respondents in

RVB participate more in FBOs, possibly because of more extension services in the basin than in BVB.

Currently, the AEA to farmer ratio in RVB (1:1,402) is higher than that of BVB (1:3000), even though they are below the recommended ratio of 1:500. Some farmers mentioned in an FGD that they are not members of FBOs due to inadequate information about joining groups and the complex processes of establishing a recognised FBO. Over 80% of respondents who join FBOs in RVB and BVB affirmed their benefits to crop production, while less than 20% consider them not beneficial.

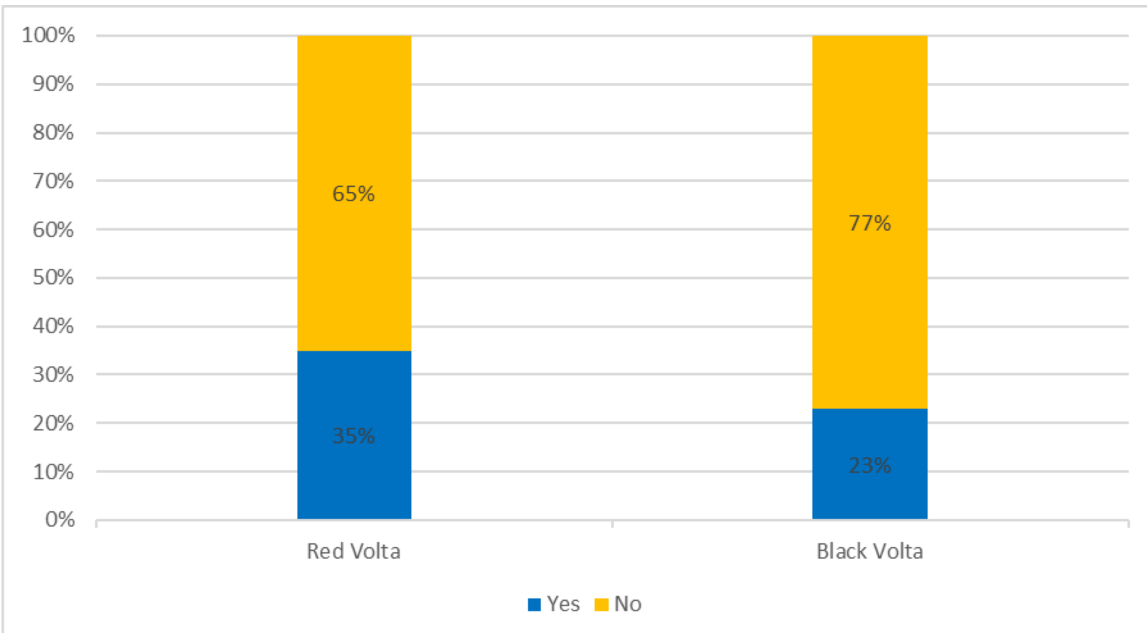

Figure 31*: 100% stacked bar chart comparing FBO participation between RVB and BVB. (Source: Field Survey, 2020).*

6.2.5.3 Access to agriculture Inputs and Services

Inputs essential for crop production in RVB and BVB include fertilizers, improved seeds, pesticides, farm tools and land, while the required services include tractor use, credit, information, storage, market opportunities and extension.

Pearson's chi-square tests show that the reported access to inputs and services patterns differ ($p \leq 0.05$) between respondents in RVB and BVB except for access to land. From **Figure 32** below, respondents in RVB are more likely than those in BVB to access inputs such as improved seeds, pesticides and farm tools, while those in BVB are more likely than those in RVB to access chemical fertilizer. An AEA explained that farmers in BVB resist improved seeds as they prefer indigenous/traditional seeds, which can be used during cultural rites like funerals, festivals and sacrifices to the gods. This background could explain why respondents in RVB tend to utilize improved seeds more than those in RVB. Access to land as input is equally available to all respondents in both basins, even though control over cropland may differ.

For agriculture services, respondents in BVB are more likely than those in RVB to access tractors, storage facilities and market opportunities, while those in RVB tend to have access to extension, credit and information than those in BVB. Commercial farming in BVB suggests farmers have more access to machinery, storage facilities and market opportunities than in RVB. However, the higher AEA to farmer ratio and more FBO participation in RVB indicates that farmers are more likely to access extension, credit and information services than those in BVB. See ***Appendix F.***

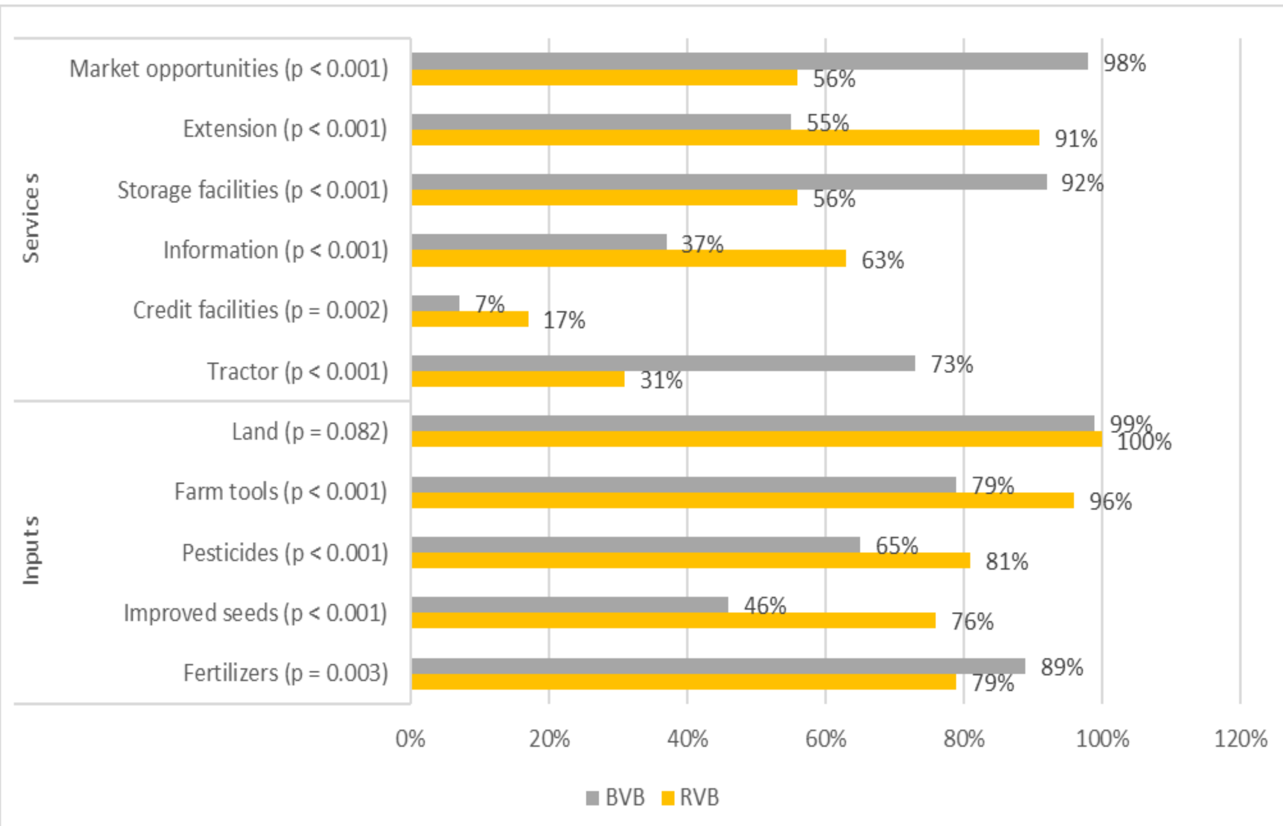

Figure 32*: Bar chart comparing respondents' who reported "yes" to access to inputs and services between RVB and BVB. (Source: Field Survey, 2020).*

Furthermore, multiple response analysis shows that respondents in RVB are more likely to access inputs and services from the government/DOA, while those in BVB tend to access these resources from the private sector (input suppliers/retailers), as shown in **Figure 33** below.

Additionally, about a third of respondents receive their inputs and services from family and friends in both basins, while only 2% receive them from NGOs in BVB. These results suggest that farmers in RVB rely more on the government for resources, while those in BVB rely on private suppliers for quick and available inputs for their commercial farming. See ***Appendix F** for details.*

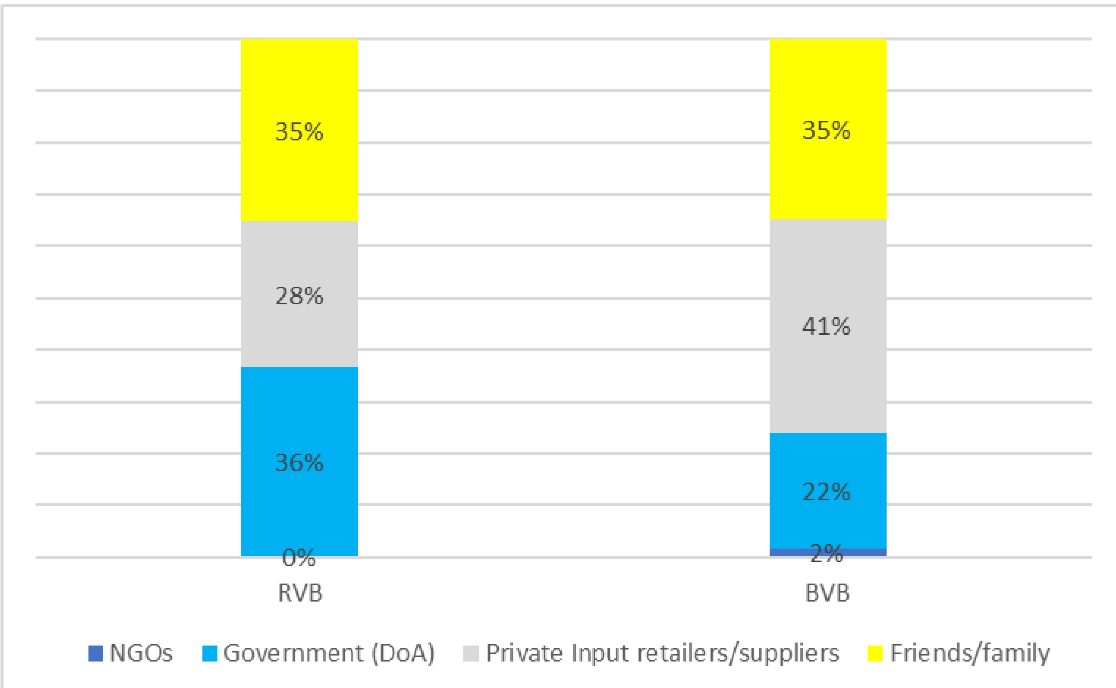

***Figure 33**: 100% stacked bar graph comparing where respondents receive their inputs and services between RVB and BVB (Source: Field Survey, 2020).*

Generally, respondents' inability to access inputs and services in RVB and BVB is due to cost, unavailability, limited supply, inadequate information, and other factors (politics and health issues), as shown in **Figure 34** below. Multiple response analysis shows that most respondents in both basins do not access inputs and services due to unavailability and cost-related challenges. The over-reliance on government-subsidised PFJ resources, which are prone to frequent delays, and smuggling (to neighbouring countries) could explain the unavailability of inputs, especially fertilisers in RVB and BVB. See ***Appendix I.***

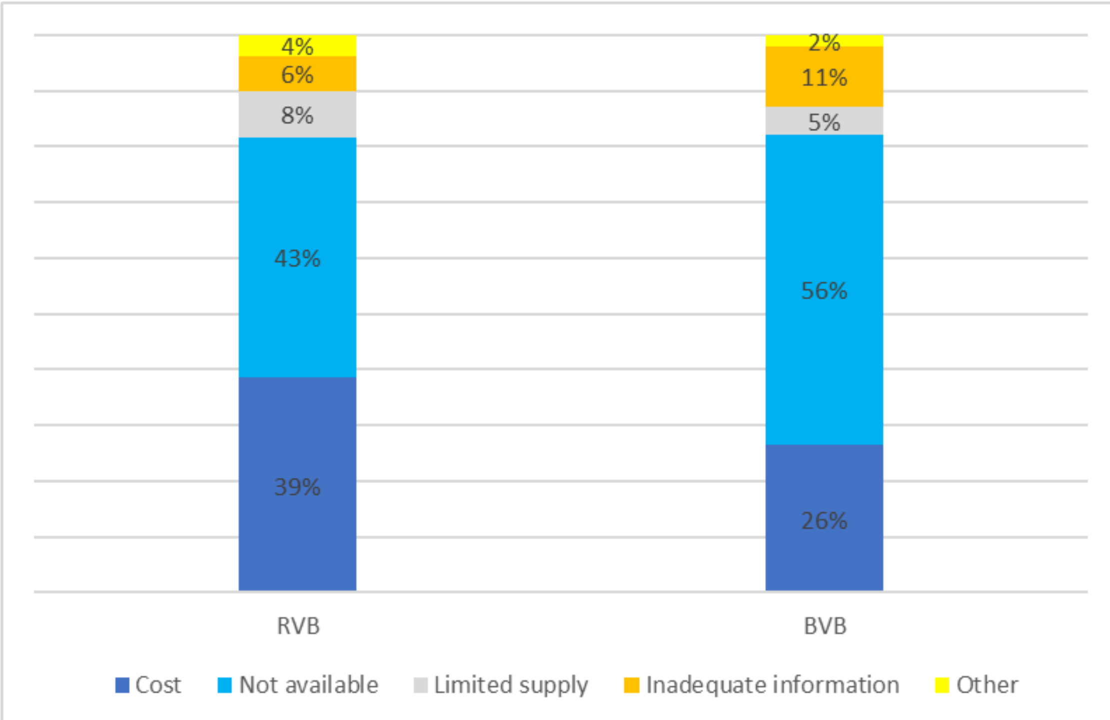

Figure 34: *100% stacked bar graph comparing respondents' inability to access inputs and services between RVB and BVB. (Source: Field Survey, 2020).*

In summary, the social and livelihood characteristics results show that farmers in RVB rely on alternative livelihood sources as off-farm activity, while those in BVB rely more on migration. FBO participation is low in both RVB and BVB, even though many respondents who are members affirm its benefits to their farming activities. Also, more respondents can access inputs and services from DOA in RVB, while those in BVB access them from input retailers. Unavailability and cost are the possible reasons respondents could not access agriculture resources in both basins.

6.3 Analysis: Determinants of socioeconomic characteristics and outcomes

The analysis section examines the relationship and associations between respondents' household/demographic (including community, age, gender and education) and socioeconomic characteristics (including cropland acquisition/size, yield levels, economic and social/livelihood outcomes/characteristics) contribute to crop productivity within basins.

6.3.1 Determinants of crop productivity outcomes

Mann-Whitney U test and Kruskal-Wallis H test examine differences and similarities between respondents' communities, education level, household dynamics, investments, FBO participation, and access to agriculture inputs/services for crop productivity outcomes, including expected yields/ha, actual yields/ha, yields/ha consumed, and yield/ha sold. Spearman's correlation and linear regression analysis also examine the strength of the relationship between crop yield/ha and relevant variables such as household size, labour size and expenditure within RVB and BVB.

6.3.1.1 Community, gender and education as determinants of crop yields

Respondents' community, gender and education are examined to identify their influence on expected and actual primary (maize) and secondary (legumes/cereals) yields in RVB and BVB. See ***Appendix H(i)*** for details.

Kruskal-Wallis H test analysis indicates that expected and actual primary yield/ha are similar ($p > 0.05$) among communities (Vea, Lungu and Beo) in RVB while differing ($p \leq 0.05$) among communities (Mettow, Zambo and Yagturi) in BVB. However, actual yields for second crops differ ($p \leq 0.05$) among communities in RVB and BVB, even though expected yields are similar ($p > 0.05$). Actual secondary crop yields/ha differ due to higher millet yields recorded in Beo of RVB and higher groundnut yields in Mettow of BVB. See **Figure 35** below. The dry season irrigation farming in Mettow enables farmers to grow more primary and secondary crops throughout the year than other communities in BVB that rely primarily on rainfed farming.

Furthermore, the Mann-Whitney U test analysis shows that expected primary ($p > 0.05$) and secondary crops ($p > 0.05$) are similar among genders in RVB and BVB. However, actual primary crop yield/ha differs ($p = 0.043$) between males and females in RVB but is similar for both genders in BVB. See **Figure 36** below. Males in RVB produce more maize yield/ha than females, possibly due to the subsistence nature of the basin's agriculture system. Males are responsible for providing food for the household and are likely to increase the primary household food crops.

Moreover, the Mann-Whitney U test analysis shows that educated respondents are more likely ($p \leq 0.05$) than less-educated respondents to have higher actual maize yields in RVB while increasing expected and actual groundnut yields in BVB. For instance, more educated respondents recorded 0.4mt/ha more actual maize yields in RVB and 0.3mt/ha more groundnut yields in BVB than less-educated respondents. See **Figure 37** below. This analysis suggests that formal education can increase crop productivity for farmers in RVB and BVB. An AEA in BVB mentioned that working with educated farmers on adopting new technology is more straightforward than with less-educated farmers since they can quickly apply written agriculture information/instructions. There is a communication challenge for some AEAs to reach less-educated farmers with local dialects instead of English, putting them at a disadvantage during training.

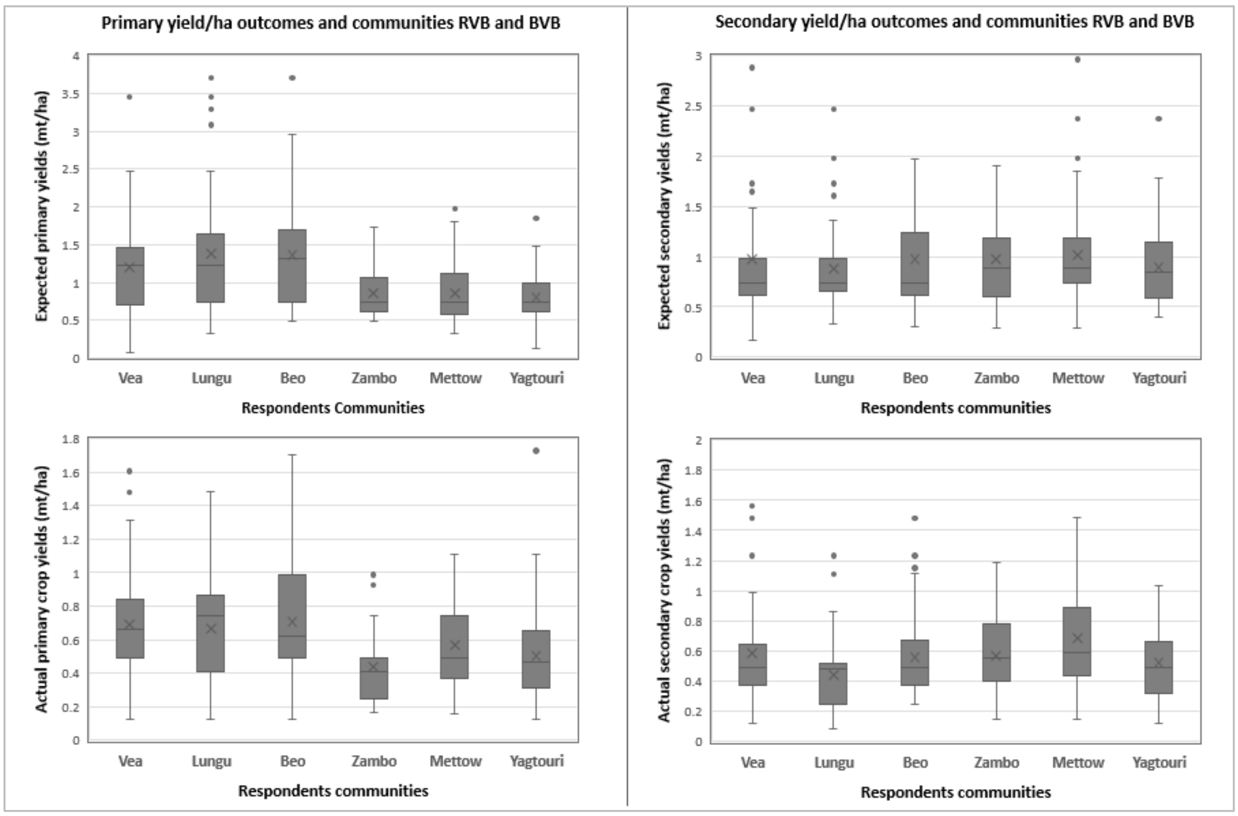

Figure 35: *Box and whisker plots showing crop yield outcomes (expected and actual) for primary and secondary crops among communities in RVB and BVB.*

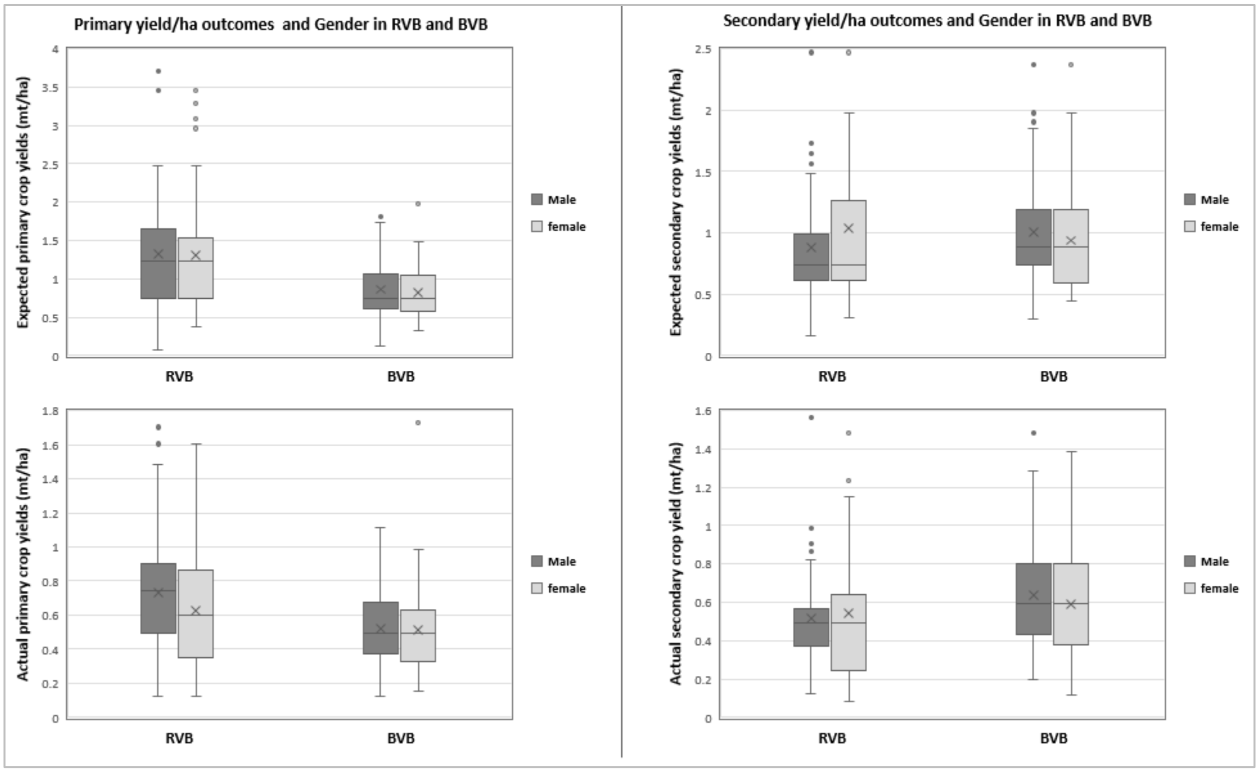

Figure 36: *Box and whisker plots showing crop yield outcomes (expected and actual) for primary and secondary crops between genders in RVB and BVB.*

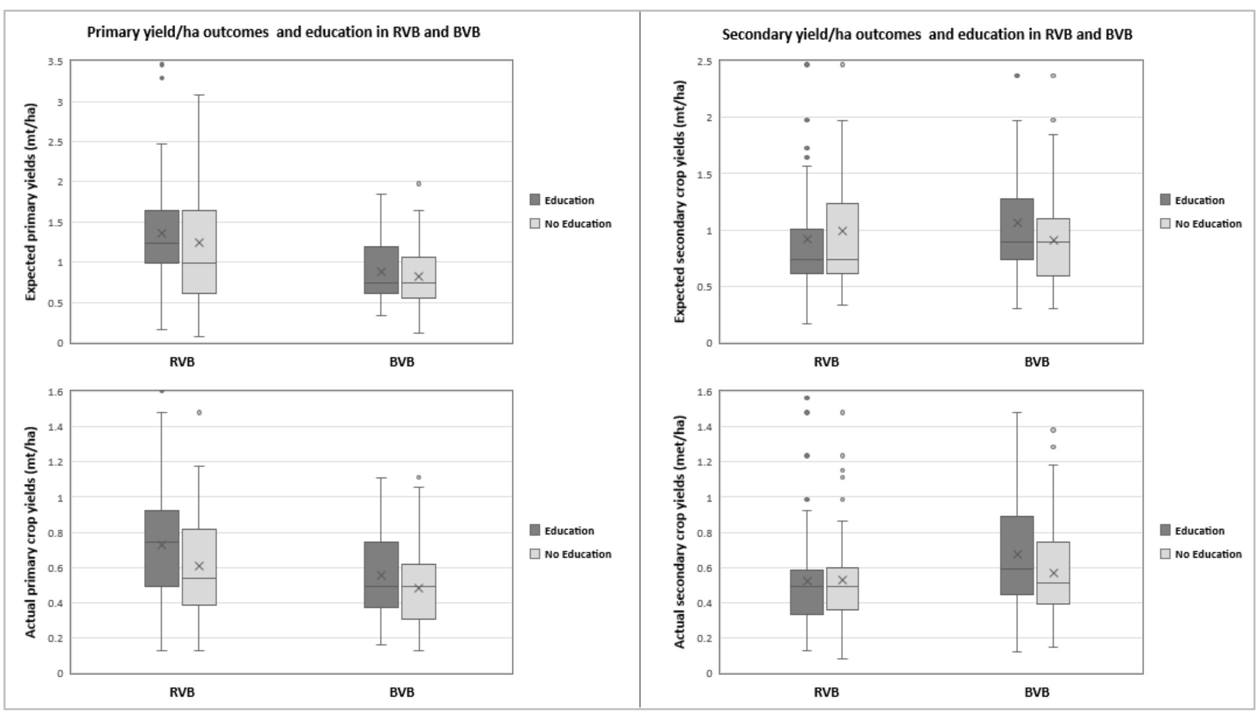

Figure 37: *Box and whisker plots showing crop yield outcomes (expected and actual) for primary and secondary crops between educational levels in RVB and BVB.*

6.3.1.2 FBO, extension service and investment as determinants of crop yields

Mann-Whitney U test analysis shows that respondents with access to FBOs are more likely than those without ($p \leq 0.05$) to increase actual primary crops (maize) in RVB and actual second crops (groundnut) in BVB. However, crop yield/ha for the secondary crops in RVB and the primary crop in BVB are similar ($p > 0.05$) between respondents with FBO access and those without access. See ***Appendix H(i)*** for details.

FBOs are usually organised and supported by extension services to enhance farmers' capacity to increase the priority crops in both basins. Interestingly, the analysis further indicates that respondents with access to extension services are more likely than those without ($p < 0.001$) to increase actual primary crops in RVB and secondary crops in BVB. Pearson's correlation indicates that access to FBO is associated with extension services in RVB ($r = 0.321$, $p = 0.02$) and BVB ($r = 0.244$, $p = 0.05$). This analysis suggests that increased access to extension services could increase maize yields in RVB and groundout yields in BVB. The possible reason for increased maize yields in RVB and groundnut yields in BVB could be that the local government has prioritised and promoted these crops through the PFJ programme.

Moreover, a simple linear regression result shows that farm expenditure can significantly predict ($p \leq 0.05$) total expected and actual yields in RVB and BVB. See **Table 47** below. The expectations and actual yields for primary and secondary crops increase when farming investments increase. Even though respondents do not meet their yield expectations, their actual yield is proportionate to the money invested per hectare. Farmers purchase inputs (seeds, fertilisers, and pesticides) and pay for services (tractor service and extension service) as farm expenditure/investment in RVB and BVB.

Table 47: *Simple linear regression analysis compares expenditure on expected and actual crop yields in RVB and BVB.*

		Unstandardized Coefficients	Std. Error	t	Sig.
Total expected yields/ha	RVB	269.437	39,018	6.906	<.001*
	BVB	139.716	49,873	2.801	0.006*
Total Actual yields/ha	RVB	383 993	69.769	5.504	<.001*
	BVB	185.179	68.284	2.712	0.007*

" denotes significance level <= 0.05"*

Also, the Mann-Whitney U test analysis further shows that respondents with access to credit facilities are more likely than those without ($p \leq 0.05$) to increase expected and actual primary yields/ha in RVB and secondary yields/ha in BVB. However, actual and expected secondary yields/ha in RVB and actual primary yields/ha in BVB are similar ($p > 0.05$) between respondents with credit access and those without access. These results suggest that farmers might access credit facilities to invest in priority crops, such as maize production in RVB and groundnut production in BVB.

6.3.1.3 Access to inputs and services as determinants of crop yields

Spearman's correlation test examines whether the total number of inputs and services respondents could access increases their overall expected and actual crop yields. The analysis assesses the actual primary and secondary crop yields to identify which crop type can be associated with the number of inputs and services respondents accessed. See **Table 48** and **Figure 38** below.

Spearman's correlation analysis shows that in RVB, the total number of inputs and services respondents access increases with reduced overall yield/ha expectations, while no relationship was found for overall actual yield/ha produced. However, in BVB, overall yield/ha expectations and actual yield/ha levels increase with increased inputs and services.

In the RVB, actual primary (maize) yields/ha reduces with an increased number of services while increasing with the number of inputs. Stepwise linear regression further shows that among inputs and services, respondents with access to information ($\beta = -0.249$, $p < 0.001$) and machinery/tractor ($\beta = -0.098$, $p = 0.035$) are likely to have reduced actual primary crop yields/ha. However, inputs like fertilizer ($\beta = 0.150$, $p < 0.001$) increase with actual primary crop yields/ha. No relationship was found between the number of services and actual secondary crop yield/ha in RVB. Nevertheless, access to storage services ($\beta = 0.155$, $p < 0.001$) could increase secondary crop yield/ha in RVB. See ***Appendix H (ii-iii)*** for details.

These analyses in RVB could be that most respondents who usually receive agriculture services cannot take action or utilize the strategies received. A community leader in Lungu explained that most NGOs and government services often target the poorest farmers with low adaptive capacity to implement strategies they receive. Increased maize yields with inputs indicate that input delivery is more effective for increasing crop yields than services provision in RVB.

However, in BVB, actual secondary crop (groundnut) yields/ha increases with the number of agriculture services and inputs. Stepwise linear regression further shows that among access to inputs and services, respondents with credit facilities (β = 0.275, p = 0.002) and improved seeds (β = 0.112, p = 0.010) are likely to have increased actual secondary crop yields/ha. See ***Appendix H(iv)*** for details. Commercial farmers in BVB invest in inputs like quality seeds and seek credit facilities to increase groundnut yields and quality to meet market demand. No relationship was found between the number of inputs or services and actual primary crop yield/ha in BVB.

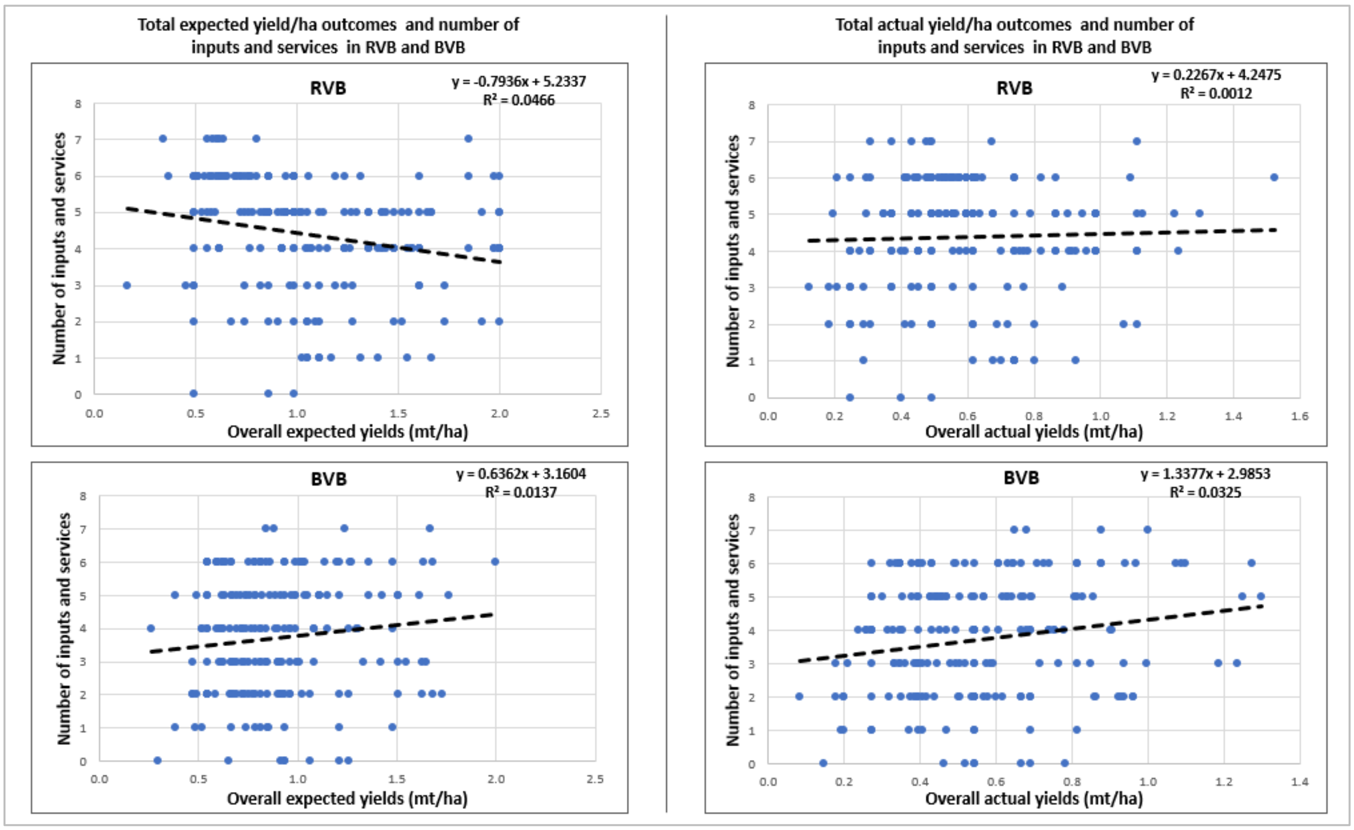

Figure 38: *Scatter plots showing the correlation between overall crop yields (expected and actual) and the number of inputs/services in RVB and BVB.*

Table 48: *Spearman's correlation analysis showing coefficient and p-values for crop yields and inputs and services in RVB and BVB.*

Correlated variables	Basin	Correlation Coefficient (r)	p-value
Total number of inputs/services and total expected crop yield/ha (primary + secondary)	*RVB*	-.321	< 0.001*
	BVB	0.250	0.036*
Total number of inputs/services and total actual crop yield/ha (primary + secondary)	*RVB*	0.053	0.467
	BVB	0.230	0.048*
Number of inputs and total actual crop yield/ha (primary + secondary)	*RVB*	0.171	0.019*
	BVB	0.109	0.129
Number of services and total actual crop yield/ha (primary + secondary)	*RVB*	-.502	< 0.001*
	BVB	0.149	0.037*
Number of inputs and actual primary crop yield/ha	*RVB*	0.183	0.01*
	BVB	0.037	0.609
Number of services and actual primary crop yield/ha	*RVB*	-.252	< 0.001*
	BVB	0.080	0.269
Number of inputs and actual secondary crop yield/ha	*RVB*	0.117	0.110
	BVB	0.165	0.049*
Number of services and actual secondary crop yield/ha	*RVB*	0.044	0.545
	BVB	0.147	0.039*

" denotes significance level <= 0.05"*

6.3.1.4 Cropland size as determinants of yield/ha levels

Multiple linear regression test examines whether the size of respondents' cropland determines their expected and actual yield levels for the primary, secondary and overall yields in RVB and BVB.

The results show that expectations for primary, secondary and overall yields/ha reduce with increased cropland size in RVB and BVB. However, besides actual primary yield/ha in BVB with no association with cropland size, the actual primary, secondary and overall yields/ha increase with increasing cropland size in both basins, as shown in **Table 49** below. These outcomes suggest that the more cropland respondents have, the more likely they could increase yields. However, in an interview, a farmer explained that he had experienced so many uncertainties with rainfall and input delays over the years that he does not look forward to favourable yields even when cropland is expanded. This anecdotal evidence suggests that yield expectations have been lower based on biophysical and socioeconomic uncertainties.

Table 49: *Multiple linear regression results showing cropland size as a determinant of expected and actual yields/ha in RVB and BVB.*

Category	Type	Basin	Unstandardized Coefficients	Std. Error	t	Sig.
Total cropland size as a determinant of Total crop Yield/ha	Expected	RVB	-1.628	0.225	-7.227	<.001*
		BVB	-0.939	0.415	-2.265	0.025*
	Actual	RVB	2.385	0.455	5.245	<.001*
		BVB	1.501	0.576	2.604	0.01*
Primary cropland size as a determinant of primary crop yield/ha (Maize)	Expected	RVB	-0.463	0.082	-5.673	<.001*
		BVB	-0.575	0.238	-2.411	0.017*
	Actual	RVB	0.884	0.185	4.766	<.001*
		BVB	0.365	0.33	1.105	0.27
Secondary cropland size as a determinant of secondary crop yield/ha (Cereals/groundnuts)	Expected	RVB	-0.805	0.137	-5.855	<.001*
		BVB	-0.281	0.156	-1.797	0.05*
	Actual	RVB	1.052	0.242	4.349	<.001*
		BVB	-0.281	0.156	-1.797	0.05*

" denotes significance level <= 0.05"*

6.3.1.5 Gender and marital status as determinants of yield consumed/sold

As noted in the results section, how respondents consume or sell crop yields is associated with the quantity they produce. Mann-Whitney U test analysis indicates that the primary crop (maize) consumption and sales between married and unmarried respondents are similar ($p > 0.05$) in RVB. However, in BVB, the primary crop consumed is higher ($p \leq 0.05$) among married than unmarried respondents, even though sales are similar ($p > 0.05$) regardless of marital status.

The analysis further shows that secondary crops (millet, sorghum and rice) consumed are higher ($p \leq 0.05$) among married than unmarried respondents in RVB, even though sales are similar ($p > 0.05$). However, in BVB, groundnut sales are higher ($p \leq 0.05$) among married than unmarried respondents, even though consumption levels are similar.

These results reemphasise the RVB as a more subsistent farming system, as most married households grow extra cereals as secondary crops to supplement maize production. In BVB, married households sell more groundnuts to earn extra cash to cater to household financial needs while cultivating more maize for household food needs.

For gender, the Mann-Whitney U test analysis indicates that males are more likely than females to increase maize consumption in RVB ($p = 0.032$) and groundnut yield sales in BVB ($p = 0.05$). However, the overall crops (maize and other cereals) sold in RVB and groundnut consumed in

BVB are similar ($p > 0.05$). These outcomes are significant because, traditionally, men are responsible for food provision and financial needs for women and children in the household. These traditional gender roles also deepen the unequal resource distribution among males and females, as most resources that come to the community may go to male-headed households rather than female-headed households.

6.3.1.6 Expenditure and FBO as determinants of yield consumed/sold

The analysis determines whether more expenditure goes towards food production for consumption purposes or the market. Spearman's correlation showed that total yield (primary and secondary crops) consumed increases with expenditure in RVB ($r = 0.533$, $p < 0.001$), while total yield sold increases with expenditure in BVB ($r = 0.30$, $p < 0.05$). No relationship was found between the total yield consumed in BVB and that sold in RVB.

Also, multiple linear regression analysis indicates that farm expenditure could be predicted ($p < 0.001$) by total yields consumed than sold in RVB, while total yield sold than consumed was a better predictor ($p < 0.001$) of expenditure in BVB, as shown in **Table 50** below.

Table 50: *Multiple linear regression analysis indicates yield/ha consumed and sold as predictors of expenditure in RVB and BVB.*

Independent variables	Basin	Unstandardised Coefficients	Std. Error	t	Sig.
Total yield consumed	*RVB*	215.897	37.713	5.725	<.001*
	BVB	57.849	53.459	1.082	0.281
Total yield sold	*RVB*	19.97	59.404	0.336	0.737
	BVB	140.722	38.246	3.679	<.001*

Dependent variable: Expenditure

" denotes significance level <= 0.05"*

The analysis suggests that farmers in RVB increase expenditure for household food consumption while those in BVB increase expenditure for the market. A farmer group leader in Beo (RVB) emphasised that crop production has always been subsistence-based due to the large size of farming households, which means that more production is consumed as food.

More, the Mann-Whitney U test identifies that respondents with access to FBO are more likely than those without ($p \leq 0.05$) to market yields than consume in both basins. However, in BVB, respondents without access to FBO are more likely than those with access ($p \leq 0.05$) to consume crop yields, mainly primary crops. This analysis suggests that farmers with FBO membership are more interested in increasing yields for the market than household consumption. A farmer group head in Mettow (BVB) emphasised this outcome in a KII.

> *"Even though our main aim is to feed our household, my farmer group is more focused on producing quality grains for market women from Techiman to buy our groundnuts and cereals. We can bargain for better prices as a group than individual farmers."*
>
> *- Farmer Group Head, Mettow Community, BVB*

In summary, respondents' community, gender, education, inputs/services accessed, FBO participation and extension services could determine expected and actual crop yields for consumption and sales in RVB and BVB. However, farmers in RVB are more likely to cultivate cereals for household use, while those in BVB focus on legume farming for the market.

6.3.2 Determinants of cropland ownership and size

As noted in section **6.3.1.4** Cropland size as determinants of yield/ha levels, respondents' cropland size could determine their crop yield levels in RVB and BVB. This sub-section examines and compares differences and similarities in cropland characteristics (ownership and size) between respondents' biographic characteristics (gender, marital status, and household leadership). The relationships between cropland size and household size are tested in both basins.

6.3.2.1 Gender, marital status and household headship as determinants of cropland ownership

Pearson's Chi-Square test shows that except for marital status, cropland ownership differs among genders and household status in RVB and BVB. See ***Appendix H** for details.*

The analysis indicates that males are more likely than females (12% in RVB and 11% in BVB) to own their cropland through direct purchase. As noted in section **6.2.1.2** Cropland ownership and size under cultivation, even though a small percentage of respondents in both basins own their croplands through purchase, more than 80% cultivate on family lands controlled by the family head, who is a male figure. In an FGD, women farmers in RVB emphasised that arable lands are unaffordable and must rely primarily on family lands for cultivation. The women added that they produce little for the market nor engage in productive off-farm activities that enable financial power to purchase croplands.

Also, between married and unmarried respondents, cropland ownership is similar across RVB and BVB. However, married women are less likely than married men ($p \leq 0.05$) to own cropland in both basins. There is no statistical difference between unmarried males and females for cropland ownership. An unmarried woman from BVB explained that she could own cropland if affordable, unlike most married women who may not own cropland even if they can afford it.

> *"As an unmarried woman, I do not receive instruction from any man on how to use my cropland. Even though I am not from this community, I purchased 4 acres (1.6 ha) of cropland. I can produce whichever crop I prefer without consulting a man/husband, which is not the same for most married women in this community."*
>
> *– Single woman, Yagturi community, BVB.*

Household heads are more likely to own croplands than household members in RVB and BVB. Household heads who own croplands are higher than household members by 20% in RVB and 15% in BVB. Household heads (often male) make decisions and control household financial resources that enable purchasing power to own croplands more than other household members, especially women farmers. Household heads are custodians of family land and can take a portion of cropland without consultation with any other household member.

Generally, a married male household head is likelier to own cropland than any other category, including unmarried household heads or members.

6.3.2.2 Cropland size and household size

Spearman's correlation is used to test the strength of the association between household size and cropland size for primary and secondary crops in RVB and BVB. The analysis shows a positive relationship between cropland size and household size for the primary crop in RVB ($r = .403$, $p < 0.001$) and BVB ($r = .387$, $p < 0.001$), as shown in ***Figure 39*** below.

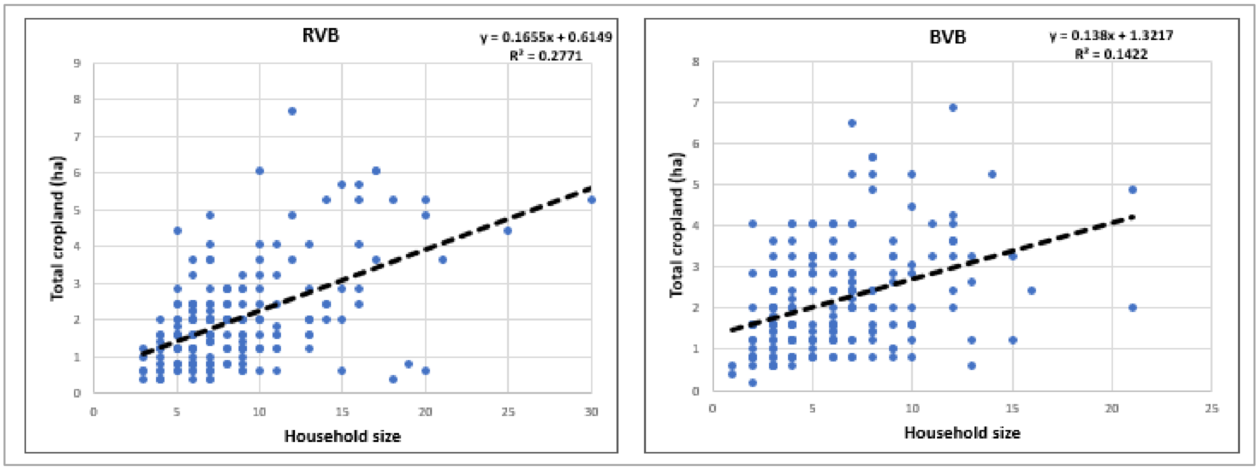

Figure 39: *Scatter plots showing the relationship between total cropland and household size in RVB and BVB.*

Again, analysis shows a positive relationship between cropland size and household size (r = .528, p< .001) in RVB and BVB (r = .221, p< .002). Large households require more food consumption than smaller households and may need more land for cultivation. While household size increases with cropland size for primary and secondary crops in both basins, the relationship is more robust for households in RVB than BVB. This outcome may be due to the differences in household size, where the average household size in RVB (9 members) is more than that of BVB (6 members).

In summary, married female farmers who are household members are less likely to own croplands than male and married household heads who may also control the distribution and allocation of family croplands besides the croplands they own. Farmers with larger households usually have higher cropland allocation than smaller households to meet consumption needs, especially in RVB.

6.3.3 Determinants of economic outcomes/characteristics

As shown in section **6.3.1.6** Expenditure and FBO as determinants of yield consumed/sold, the increased farm expenditure could increase relevant crop yields/ha in RVB and BVB for consumption and market. Farmers mobilise capital for farm investment through commercial farming, off-farm activities and savings and loan schemes. Mann-Whitney U test and Kruskal-Wallis H test examine differences and similarities between respondents' community, gender, age, marital status and education for economic variables such as expenditure, yield incomes, off-farm incomes and savings and loans. Spearman's correlation and regression analysis also examine the strength of the association between economic variables and other critical variables within the basins.

6.3.3.1 Relationship between expenditure, income and profit/losses on crop yields

Spearman's correlation shows that farm expenditure increases with incomes from yield sold in RVB ($r = .584$, $p < 0.001$) and BVB ($r = .524$, $p < 0.001$). This result suggests that yield incomes could increase significantly with adequate investment in farming. Farmers with commercial intentions often invest more for higher incomes, especially groundnut production in BVB.

However, increasing investment could also lead to losses in RVB ($r = -.444$, $p < 0.001$) and BVB ($r = -.456$, $p < 0.01$) after expenditure is subtracted from yield incomes. This analysis suggests that farm expenditure is higher than the income from commercial farming leading to losses in both basins.

Moreover, the correlation analysis shows that increased yield incomes slightly increase profits in RVB ($r = .408$, $p < 0.01$) and BVB ($r = .430$, $p < 0.001$). The rationale is that even though farmers in BVB appear to be more commercial, both basins increase expenditure to increase yield incomes. Multiple linear regression results confirm correlation analysis indicating that expenditure and incomes can predict yield profits/losses in RVB and BVB, as shown in **Table 51** below.

Table 51: *Multiple linear regression showing farm expenditure and yield income as predictors of yield profits/losses in RVB and BVB.*

Basin	Determinants	Unstandardized Coefficients	Std. Error	t	Sig.
RVB	*Farm expenditure*	-0.497	0.036	-13.797	<.001*
	Yield Income	0.327	0.022	14.523	<.001*
BVB	*Farm expenditure*	-0.215	0.017	-13.017	<.001*
	Yield Income	0.225	0.013	17.953	<.001*
Dependent Variable- Profit/Loses					

" denotes significance level <= 0.05"*

6.3.3.2 Gender, age and education as determinants of commercial agriculture

Mann-Whitney U test analysis showed that except for expenditure in BVB ($p \leq 0.05$), expenditure, incomes and profit/losses between males and females are similar ($p > 0.05$) in RVB and BVB. *See **Appendix H(v)** for details.* Women in BVB emphasised that, unlike males, they lack the financial capability to invest in commercial farming, such as purchasing fertilizers or hiring a tractor for land preparation before planting. Female farmers prioritize subsistence agriculture over commercial because they take responsibility for finding food for the household when men fail to provide.

> *"As women, we prepare meals to feed our household even when our husbands do not provide any crops for food. We cannot make our children starve, so we prioritise growing to feed our families when farming and growing crops."*
>
> *– Women FGD, Mettow Community, BVB.*

In addition, the Mann-Whitney U test analysis reveals that educated respondents are more likely than less-educated ($p \leq 0.05$) ones to have higher yield incomes in RVB while increasing expenditure and incomes in BVB. *See **Appendix H(v)** for details.* Educated respondents often have formal employment that enables them to increase farm investment and yield incomes in BVB. However, educated respondents are more widespread in RVB than BVB, so RVB may not influence farm expenditure.

Also, Mann-Whitney U test analysis indicates that except for profits/losses ($p > 0.05$), young respondents are more likely than elderly respondents to increase expenditure and yield incomes in both basins. See ***Appendix H(v)*** *for details.* Youthful respondents often engage in off-farm activities like migration during the dry season to raise capital for farming during the rainy season. Also, young farmers are more commercially active than older farmers in searching for new market opportunities, especially for the BVB.

6.3.3.3 Extension service and FBO as determinants of commercial agriculture

Mann-Whitney U test shows that respondents with access to extension services are more likely ($p \leq 0.05$) to increase farm expenditure and income than profits/losses in BVB, while expenditure, incomes and profits/losses are similar regardless of extension access in RVB. See ***Appendix H(v)*** *for details*. These results reemphasise the commercial system in BVB, where extension support goes to commercial groundnut farmers. Moreover, extension services are more accessible to farmers in BVB than in BVB, where farmer groups are often the primary recipients.

Furthermore, Mann-Whitney U test analysis shows that respondents with FBO are more likely ($p \leq 0.05$) to increase farm expenditure and yield incomes in RVB and BVB. See ***Appendix H(v)*** *for details.* As indicated earlier in this section, FBOs are helpful channels for farmers to access adequate financial and extension services to prioritize essential crops (maize and groundnuts), leading to higher yields and incomes in RVB and BVB.

6.3.3.4 Community, gender and education as determinants of Off-farm income

Kruskal-Wallis H test shows that respondents' communities can influence ($p \leq 0.05$) the amount received as alternative livelihoods incomes and remittances in RVB, while communities in BVB are similar for alternative livelihood income and remittances. See ***Appendix H(vi)*** *for details.* Respondents in Lungu of RVB have higher average off-farm incomes, possibly due to lower on-farm incomes than Beo and Vea, and as such, engaging in more alternative livelihood and migration activities.

Again, Mann-Whitney U test indicates that males are more likely than females ($p \leq 0.05$) to have higher off-farm income in BVB, while incomes are similar ($p > 0.05$) among genders in RVB. See ***Appendix H(vi)*** *for details.* Males tend to engage in seasonal migration, petty trading and paid labour (including formal employment) more than females in BVB. However, in RVB, various NGO initiatives work with women groups on alternative livelihood sources like weaving and livestock rearing. A local NGO lead explained that women's groups receive support annually to raise small ruminants, process shea butter, and produce textiles to generate income. However, a community leader in BVB complained that prioritising women over men affects vulnerable men with low adaptive capacity against biophysical risks, including erratic rainfall and poor soils.

More educated respondents are more likely than less-educated ($p \leq 0.05$) to increase off-farm incomes in RVB and BVB. See ***Appendix H(vi)*** *for details.* Educated respondents often have formal employment opportunities to increase off-farm incomes. In a KII, a community leader in BVB explained the access to more off-farm incomes.

> *"Even though I consider myself a farmer first, I receive a significant annual income from my salaried work as a pupil's teacher. I do farm work to provide food for my family and contribute to community and family events".*
>
> *– A farmer and Teacher, Beo Community, RVB.*

For instance, alternative livelihood incomes from tertiary-educated respondents (GH2300) are almost five times higher in RVB and three times higher (GH 1000) in BVB than less-educated respondents. However, remittances for tertiary-educated respondents are the least (about GH 100) in RVB and the highest (GH 725) in BVB. A possible reason for low remittances from tertiary-educated respondents in RVB could be satisfied with alternative livelihood incomes, while those in BVB require remittances to supplement alternative livelihood incomes.

6.3.3.5 Savings and loans towards expenditure

Multiple linear regression analysis shows that loans are better predictors ($p \leq 0.05$) of farm expenditure than savings in RVB, while loans and savings are better predictors of farm expenditure in BVB, as shown in **Table 52** below. These results suggest that respondents use loans to invest in farming than their savings in RVB, while those in BVB use both loans and savings as investments in farming. Commercial farming in BVB requires capital from different sources to increase yields and incomes. However, some farmers may borrow money from VSLAs to increase farm expenditure for household food crops, especially RVB. For instance, an NGO leader in RVB mentioned that the UNDP had supported vulnerable farmers through the Women in Agriculture Programme (WAP) with about GH 100,000 after successfully managing GH 50,000 received two years earlier. These monies are given as soft loans with no interest to support women in agriculture and other livelihood activities.

Table 52*: Multiple Linear regression showing loans and savings on expenditure in RVB and BVB*

Basin	Determinants	Unstandardized Coefficients	Std. Error	t	Sig.
RVB	*Loans*	0.455	0.153	2.972	0.007*
	Savings	0.361	0.26	1.388	0.18
BVB	*Loans*	0.774	0.242	3.203	0.004*
	Savings	0.34	0.108	3.163	0.005*
Dependent Variable - expenditure on crops production					
Significance level ($p \leq 0.05$*)					

In summary, respondents in RVB and BVB are more likely to increase their incomes and profits when their farm expenditures are increased. Young, educated males with access to extension and FBOs are more likely to increase expenditure and yield incomes, especially in BVB. Due to commercial activities in BVB, respondents seek more remittances, loans and savings to invest in farming for higher returns than in RVB. However, respondents in RVB are more likely than BVB to increase alternative incomes to supplement subsistent farming.

6.3.4 Determinants of social characteristics

Pearson's Chi-square test and logistic regression examine and compare determinants of social characteristics, including off-farm activities, FBO participation, migration and access to inputs and services for crop productivity in RVB and BVB.

6.3.4.1 Gender, education and household size as determinants of alternative livelihood sources

Pearson's chi-square analysis shows that females are less likely than males to have an alternative livelihood source in RVB and BVB. For instance, 32% and 48% of females in RVB and BVB do not have any alternative livelihood source compared to 20% and 35% of males in RVB and BVB. However, females are more likely to dominate alternative livelihood sources such as petty trading, handicraft and food processing, while males dominate paid labour. In BVB, more females engage in petty trading and food processing, while males are engaged in handicrafts and paid labour.

Further chi-square analysis shows that educated respondents are more likely ($p \leq 0.05$) to engage in paid labour than less-educated respondents, who are more likely to engage in petty trading in both basins. For instance, 35% and 43% of educated respondents in RVB and BVB do paid labour, while 40% and 61% of less-educated respondents in RVB and BVB do petty trading. These results suggest that educated respondents tend to take formal employment opportunities as paid labour than less-educated respondents, especially in RVB

Moreover, Spearman's correlation analysis shows that the number of alternative livelihood sources increases slightly with household size in RVB ($r = 0.253$, $p < 0.001$) and BVB ($r = 0.289$, $p < 0.001$). This outcome suggests that farmers seek more livelihood options besides farming to increase incomes when household size increases.

6.3.4.2 Age, gender and education as determinants of migration

Pearson's chi-square test found that older respondents are more likely ($p \leq 0.05$) to migrate frequently in RVB and BVB. For instance, 48% and 57% of elderly respondents in RVB and BVB frequently migrate, compared to 30% and 42% of the youth in RVB and BVB who also frequently migrate. However, young respondents are more likely ($p < 0.001$) to benefit from migration than older respondents in RVB and BVB. About 90% of the youth in RVB and BVB indicated migration is a beneficial activity, while below 50% of elderly respondents reported the same. These results suggest that older migrants may have more migration experience than younger migrants, explaining the higher frequency in RVB and BVB. However, younger respondents may benefit from the pleasure of new migration experiences like urban life rather than financial rewards/remittances ($p > 0.05$), which are the same regardless of age in RVB and BVB.

Gender does not determine migration frequency ($p > 0.05$) in RVB and BVB. However, about 60% of males and females in RVB migrate less frequently, while about 50% of males and females in BVB frequently migrate. Generally, respondents in RVB are more likely to migrate less than those in BVB, explaining why both genders in RVB also migrate less frequently. Males in BVB are more likely to practice seasonal migration (which is more frequent) than females, who practice permanent migration. Young men in Mettow (BVB) lamented that they could not find partners due to young women migrating to new locations to settle permanently.

Further chi-square analysis shows that less-educated respondents are more likely than educated ones ($p \leq 0.05$) to migrate frequently in RVB, while educated respondents frequently migrate than less-educated ones in BVB. For instance, about 70% of tertiary-educated respondents in RVB never migrated compared to 80% of less-educated respondents who migrated frequently. Nevertheless, about 70% of tertiary-educated respondents frequently migrate compared to 50% of less-educated respondents who migrate less frequently. These outcomes suggest that tertiary-educated respondents in RVB may be more satisfied with off-farm incomes than less-educated respondents who combine multiple off-farm activities, including migration, to supplement household incomes. The outcome in BVB suggests fewer formal employment opportunities for respondents with higher education, enabling migration. A farmer group leader explained in a KII that unemployment is the cause of migration among the educated in BVB.

"Ever since my daughter graduated from the University of Development Studies, she could not find any decent job in the Municipality (Lawra Municipality), so she had to travel often to the city (Wa) to look for job opportunities which are usually temporary and less rewarding".

Farmer group Leader, Mettow community, BVB

Furthermore, the nearest city for migrants in BVB is Wa, about 90km away from BVB, while the nearest city for migrants in RVB is Bolgatanga, about 16km away. The distance from the nearest city means that respondents in RVB could work daily in Bolgatanga and live in their communities, while those in BVB may temporarily or permanently work and live in Wa.

6.3.4.3 FBO participation and access to agriculture inputs and services

Pearson's chi-square tests examine which agriculture input or service could be associated with joining FBO. **Table 53** below displays the crosstabulation percentages and P-value of the Chi-square test results for RVB and BVB.

Table 53*: Percentages and P-value results for FBO membership and access to inputs and services in RVB and BVB*

Category	Access type	*Basin*	% Access within FBO	% Access without FBO	P-Value
Inputs	Fertilizers	*RVB*	93%	64%	0.002
		BVB	100%	77%	0.013
	Improved seeds	*RVB*	88%	62%	0.011
		BVB	65%	32%	0.006
	Pesticides	*RVB*	96%	66%	0.001
		BVB	81%	52%	0.021
Services	Extension	*RVB*	100%	77%	0.002
		BVB	68%	42%	0.050
	Credit	*RVB*	12%	19%	0.237
		BVB	24%	5%	0.040
	Market	*RVB*	46%	71%	0.050
		BVB	100%	99%	0.437

" denotes significance level <= 0.05"*

Respondents with FBOs are more likely than those without to access all agriculture inputs in RVB and BVB. Respondents with FBOs are 29%, 26% and 30% higher in accessing fertilizers, improved seeds and pesticides than those without in RVB, while respondents with FBOs are 23%, 33% and 29% higher in accessing fertilizers, improved seeds and pesticides than those without in BVB. As discussed earlier, organized farmer groups make distributing resources easier across communities, especially government-subsidised inputs, and could explain why farmers with FBOs are more than those without more input access.

Unlike inputs access, an FBO membership does not always increase ($p > 0.05$) in agriculture services in RVB and BVB. Respondents with FBOs and without differ ($p \leq 0.05$) for extension and market but are similar for credit in RVB, extension and credit differ but are similar for market services in BVB. Respondents in RVB with FBOs are 19% higher to access credit facilities than those without, while respondents in BVB without FBOs are 25% higher to access market services than those with FBOs. The possible reasons respondents without FBOs are more likely to access market services than those with FBOs could be the commercial-oriented FBOs in RVB, where groups wait for better market prices before sales, unlike subsistence farmers selling surplus yields regardless of market prices. Access to credit facilities is generally poor regardless of FBO membership in RVB and BVB.

All respondents in RVB with FBOs had access to extension services compared to 68% in BVB. RVB DOA trains more assistant AEAs from FBO leaders to support extension services than in BVB. DOA report shows that in 2020, 15 FBO leaders were trained as AEA assistants in RVB, while in BVB, no FBO leader was trained due to the low capacity to conduct such training.

6.3.4.4 Community, gender and education as determinants of input access

Pearson's chi-square analysis shows that access to inputs in RVB communities differs ($p \leq 0.05$) for fertilizers but is similar for improved seeds and pesticides, while access to inputs in BVB communities differs ($p \leq 0.05$) for fertilizer and pesticides but is similar for improved seeds. In RVB, respondents without access to fertilizers are more in Lungu (35%) than Beo (19%) and Vea (5%), while those in BVB with access to fertilizers are more in Mettow (95%) than Zambo (88%) and Yagturi (82%). Generally, more respondents in Vea (RVB) and Mettow (BVB) access inputs than other communities due to active dry season irrigation farming, which attracts more input suppliers. However, Lungu (RVB) and Zambo (BVB), with the least crop yields, have the least access to inputs.

Further Chi-square analysis shows that access to fertilizers, improved seeds and pesticides are similar ($p > 0.05$) between males and females in RVB, while males are more likely than females ($p \leq 0.05$) to access fertilizers, improved seeds, and pesticides in BVB. Even though access to inputs is similar between genders, males are about 5% higher to access fertilizers and improved seeds than females in RVB. In BVB, males are 10%, 15%, and 18% more to access fertilizers, improved seeds and pesticides than females. The private sector supplies most inputs in BVB, which are more expensive than PFJ-subsidised inputs supplied in RVB. Moreover, females in BVB have less on-farm and off-farm incomes to access these inputs than their male counterparts. For instance, more females (66%) than males (30%) in BVB could not access fertilizers due to cost. A female farmer from Yagturi (BVB) emphasized that fertilizers and improved seeds are expensive and compete with household needs like the cost of basic needs.

> *"I find it difficult to raise enough money to purchase fertilizers, improved seeds, and pay for labourers to work on my farm because I have to use the*

same money I receive from VSLA to purchase extra food when needed, pay health insurance, and pay health insurance to provide my children's needs".

- *Female Farmer and widow, Yagturi community, BVB*

Moreover, chi-square analysis shows that, except for pesticide access in BVB, educated respondents are more likely than less-educated ones ($p \leq 0.05$) to access fertilizers and improved seeds in RVB and BVB. Educated respondents in RVB are 12%, 14% and 13% more to access fertilizers, improved seeds and pesticides than less-educated ones, while educated respondents in BVB are 10% and 15% more to access fertilizer and improved seeds than less-educated ones. The higher a respondent's education, the higher the on-farm and off-farm incomes to access inputs. For instance, more less-educated (56%) than educated (30%) in BVB noted that they could not afford to purchase inputs.

6.3.4.5 Community, gender and education as determinants of agriculture services

Pearson's chi-square shows that except for extension services, access to information, machinery/tractor, and credit differ ($p \leq 0.05$) between communities in RVB, while in BVB, access to information, machinery/tractor, and credit are similar ($p > 0.05$) among communities except for extension services. For instance, information access in RVB is 32% more in Vea than in Lungu, while machinery services are 24% more in Beo than in Lungu. In BVB, respondents with access to extension services in Mettow are 31% more than those in Zambo. Like access to agriculture inputs, the Lungu (RVB) and Zambo (BVB) communities have the least access to agriculture services than Vea (RVB) and Mettow (BVB), with the most access to agriculture services. Vea and Mettow have an advantage in active dry-season irrigation farming, as most services are concentrated in those communities. In RVB, an average of 90% and 50% of respondents in all three communities have access to extension and market services, respectively.

Further chi-square shows that males and females farmers in RVB have access ($p > 0.05$) to information, machinery, credit, extension, and market, while males in BVB are more likely than females ($p \leq 0.05$) to access information, machinery and extension services except for credit and market services. However, access to credit and tractor services in BVB is deficient (below 30%), while extension services are higher (above 90%) for both genders. Males in BVB are 10%, 12% and 20% higher than females to access extension, tractor and information services. For information delivery in BVB, a binary logistic regression analysis showed that owning a mobile phone can better predict ($p = 0.002$) respondents' access to information services than owning a television, radio or internet as assets. More females (24%) than males (8%) in RVB do not own a mobile phone (24%), making it challenging to access weather and market services.

Also, chi-square analysis shows that, except for information access ($p \leq 0.05$), educated and less-educated respondents access machinery, extension, credit facilities and markets in both basins. Educated respondents are 18% more in RVB and 15% in BVB to access information than less-educated ones. Educated respondents have access to information from different communication channels, including the internet, while less-educated respondents are often limited to radio, mobile phone and in-person engagements. For instance, tertiary-educated respondents with internet access are 47% more in RVB and 40% more in BVB than less-educated respondents. About 80% of tertiary-educated with internet access indicated the benefit of accessing information for farming. A tertiary-educated respondent in RVB indicated that browsing the internet for new ideas/information to practice has helped adopt new farming strategies/technologies.

> *"Having internet access has been useful, especially in finding new technologies and ideas for the next farming season. I came across a planting technique on Facebook last year, and I tried it on my farm this year, and it worked". Also, when the extension office introduces new inputs, especially agrochemicals, I check online to learn how to apply these chemicals.*
>
> - *Tertiary-educated Farmer, Beo community, RVB*

In summary, social/livelihood characteristics, including access to off-farm activities, inputs and services, are influenced by respondents' community, gender and education. Males are more likely than females to access off-farm activities (alternative livelihood sources and migration), inputs and services primarily in BVB. Also, educated respondents in both basins could access higher-paying off-farm activities and more inputs and services than less-educated ones. Furthermore, respondents with access to FBOs are more likely to access essential inputs (fertilizers, improved seeds and pesticides), extension services, credit facilities in BVB and market services in RVB.

6.4 Discussion: Socioeconomic characteristics as enablers of SI goals/principles

This objective aims to assess and compare the socioeconomic determinants of crop productivity and livelihoods as enablers or barriers to SI goals in semi-arid smallholder crop production systems in RVB and BVB of Northern Ghana. The themes for discussion are the SI goals of productivity, resilience, efficiency, and equity. The goal is to know how smallholder farmers' socioeconomic characteristics and livelihood outcomes, including access/use of cropland, crop yields, expenditure/incomes, off-farm activities and resources (inputs and services), could hinder or enhance productivity, resilience, efficiency and equity goals for SI in RVB and BVB. This section discusses the present study's findings alongside evidence from previous research conducted in Northern Ghana/West Africa and their implications for SI. Based on the findings, practical recommendations are made for policy, practice, and research to achieve SI goals in Northern Ghana/West Africa.

6.4.1 Socioeconomic characteristics of crop productivity in semi-arid Ghana

Crop production in semi-arid West Africa is characterised in most literature as a factor of biophysical and socioeconomic interaction that define yield levels for most farmers (Jalloh et al., 2012; Zougmoré et al., 2014). Yield levels, incomes and utilisation (market and consumption) are the productivity outcomes considered in this study. The socioeconomic characteristics that determine these productivity outcomes include crop types, landuse, FBO membership, investments, cropland size, household size, education, extension and access to resources.

The findings have shown that farmers in both basins could not meet their potential yields for most crops; however, those in RVB tend to increase primary crop (maise) yields, while those in BVB were more likely to increase secondary crop (groundnut) yields. A World Bank report aligns with the study's findings by indicating that crop yields, especially for cereals, have been about 60% less than their potential in Northern Ghana (World Bank, 2017). The findings further indicate that farmers in RVB were more likely to practice subsistence farming by consuming more yields (primary and secondary), while those BVB tend to engage in commercial farming, selling more secondary yields (groundnut). The differences in farming types between basins could be due to the differences in household needs, as farmers in RVB may require more food crops to feed their large household/population density than those in BVB who could afford to combine subsistence and commercial farming. These findings are consistent with a previous study that showed that cereals are predominantly grown for household food needs, while legumes are cultivated with a commercial interest in Northern Ghana (Mzyece, 2021).

Another important finding from the study showed that farmers in both basins could increase yields, incomes and utilisation for important crops by increasing expenditure/investments and participating in FBOs. For instance, access to credits and loans was found to be the critical sources of investment that enabled yield increases in both basins. Investments allow farmers to purchase inputs such as improved seeds and fertilisers that enhance productivity. This finding is consistent with the existing research suggesting that access to capital/credit or some form of wealth enhances investments in new technology and strategies that increase yields (Amegnaglo, 2018; S. A. Wood et al., 2014). Other factors such as access to large cropland, education and extension (only in BVB) tend to enable farmers to increase yield and income levels. Previous studies show that farmers with education and extension services can implement crop management strategies that could enhance biophysical properties to increase productivity (Deressa et al., 2011; Tesfahunegn et al., 2021). However, increasing yields with accompanying land expansion to meet growing household food demand could further degrade fragile semi-arid agriculture systems, weakening national sustainability efforts.

Further findings from the present study show that farmers in both basins with access to dry season irrigation and FBOs are more likely to increase yields and sell some of their production. For instance, farmers with access to dry-season farming, especially in the Mettow community in BVB, could increase actual yields for both primary and secondary crops. This finding aligns with previous research suggesting that farmers' access to dry-season irrigation farming can increase productivity and enhance food security in SSA (MacCarthy et al., 2018; Schindler, 2009). However, farmers without FBOs and communities without dry-season irrigation farming were more likely to consume their yields than send them to the market, especially in BVB. These findings suggest that most farmers join FBOs in irrigated communities for commercial than consumption reasons. According to Namara et al. (2011), the most successful commercial irrigation farming systems in Northern Ghana are FBO-oriented. These FBOs go into contractual agreements with out-grower schemes that guarantee access to input, extension services, and a ready market for cultivating crops under required specifications (Namara et al., 2011).

Surprisingly, the study found that access to agriculture services like information and tractor use decreases crop yields in RVB, while farmers in both basins with access to inputs like fertilisers (RVB) and improved seeds (BVB) increased yield levels to meet household food and commercial needs. Evidence shows that the quality of government extension services affects the overall productivity level in SSA as most services target farmers who cannot use the information received (World Bank, 2017). However, other studies in Northern Ghana support the present study's findings, indicating that increased inputs like fertilisers and improved seeds can also increase crop yield (van Loon et al., 2019; Zougmoré et al., 2016).

6.4.2 Resilience through farm expenditure and off-farm activities

The environmental and socioeconomic challenges in the agriculture system require multiple strategies at different levels that enable farmers to build resilience and enhance crop productivity in West Africa (ADB & FAO, 2015; Partey et al., 2018). The present findings have indicated that the socioeconomic and livelihood characteristics, including financial resources (farm expenditure, off-farm incomes, savings and loans) and off-farm activities (alternative livelihood options and migration), could enable or hinder farmers from building resilience against crop production risks which are critical to enhancing productivity in RVB and BVB.

On financial resources for building resilience, the study found that farmers in both basins invest a similar amount of capital to purchase inputs, hire services and practice on-farm strategies. Similarly, Rosenstock et al. (2018) found that farmers increase on-farm technology/strategy adoptions with increased investments. Adaptive capacity to water and soil risks are better with increased investments as farmers can secure more efficient technologies like precision farming for irrigation and drought-resistant seeds (Partey et al., 2018; Rosenstock et al., 2018). The study's findings further proved that farmers with high savings also increase farm expenditure in BVB, while the loan amount received increases with expenditure in both basins. Even though loans could increase farm investments in both basins, fewer farmers could access loan services. However, farmers in RVB tend to save more and receive more loans than those in BVB. Some financing schemes, including VSLAs, offer loans to farmers relative to the amount saved with the scheme. According to Lawson et al. (2020), savings and loan schemes enable farmers, especially women, to manage on-farm biophysical risks by hiring labour or machinery (tractor services) for farm work. However, some scholars have argued that cost-sharing financing schemes like subsidies are better ways of enabling farmers to adopt strategies/technologies that enhance resilience than loan services (Rosenstock et al., 2018).

Another form of increasing farming expenditure is through alternative livelihood incomes and remittances. According to Marchetta (2013), farmers in Northern Ghana often complement yield incomes with revenues from alternative livelihood activities and out-migration. The study found that farmers in RVB are more likely than farmers in BVB to receive alternative livelihood incomes and remittances for farm investments. Even though the amounts received as alternative livelihood incomes in RVB were higher, those received as remittances in BVB doubled that of RVB. In a similar study, Rao et al. (2019) found that fewer alternative livelihood options in the BVB trigger farmers, especially men, to seek income through seasonal migration to southern parts of the country.

Off-farm income-generating activities enable increased farming investments and livelihood diversification from on-farm activities, reducing vulnerability to biophysical risks and enhancing resilience for farming households. The findings from this study showed that while farmers in the RVB are more likely to engage in alternative livelihood sources, those in BVB tend to engage in migration as an off-farm coping mechanism from on-farm work. For instance, farmers from Lungu with the lowest crop yields in RVB also have more alternative livelihood options, while those in Yagturi with the lowest yields in BVB have the highest percentage of farmers who migrate or are without any alternative livelihood options. These results highlight how farmers' alternative livelihood options and migration are used in different communities to cope with on-farm risks. Previous work in Northern Ghana suggests farmers will likely diversify livelihoods as a resilient strategy against potential crop failure (Lolig et al., 2014; Rosenstock et al., 2018). The findings from this study further show that migration is an important part of livelihood options in both basins, even though more farmers in BVB tend to perceive it as beneficial, while those in RVB consider it unbeneficial activity. This finding in BVB may be due to high remittances and technology transfer from cities to improve commercial farming, while those in RVB may not find any relevance to subsistence farming. However, the finding in RVB may be consistent with studies from Northern Ghana showing that households lose active labour force to out-migration affecting the adoption of labour-intensive strategies that could enhance resilience and productivity (Dakyaga et al., 2020a; Namara et al., 2011).

6.4.3 Enhancing farm efficiency through agriculture services and farmer groups

Agriculture system efficiency preventing waste requires FBO support and agriculture services (extension, machinery, storage, market, information and credit) that enable effective use of farm inputs (fertiliser, improved seeds, farm tools, land and agrochemicals) to build resilience and increase productivity.

The findings from the present study show that over 80% of farmers in both basins considered FBOs beneficial for adopting on-farm strategies and accessing extension services, inputs and information while increasing yields, incomes and profits. Several studies have established that effective FBO platforms enable smallholder farmers to learn new skills and adopt technologies to efficiently manage risks (Addai et al., 2022; Anang & Asante, 2020; A. Salifu & Funk, 2012). Regardless of FBO benefits, farmers' participation is not encouraging in both basins, even though more farmers in RVB tend to join FBOs than those in RVB. Salifu and Funk (2012) identified that the process required to establish or formalise FBOs, such as drafting a constitution, opening a bank account, registration payment and election of leaders, may be hectic for some farmers to form such groups. This finding supports previous evidence suggesting that smallholder farmers, especially in BVB, lack organised groups and rely on the community social pool for the capacity to practice farm strategies, including land preparation, planting and harvesting (Dakyaga et al., 2020a; A. Salifu & Funk, 2012).

Another important finding identified in the study indicated that farmers in BVB are more likely to have access to machinery (tractor), storage and market services, while those in RVB tend to access extension, credit and information services. Agriculture extension is the most sought-after essential service for farmers to access subsidised agriculture resources (improved seeds, fertilisers, information and machinery), especially in RVB. However, one-third of farmers in both basins receive support services through friends/family in the form of a social pool for adopting labour-intensive strategies such as land preparation and harvesting. The social pool support system is common in Northern Ghana, where members from different households rotate to help with ploughing, weeding, planting, fertilising, and harvesting. Receiving services from family/friends instead of extension services could hinder farmers from efficiently using available inputs to enhance yields. Some farmers could not access extension services in both basins due to their unavailability or the cost involved in paying for such services when they are available. Some NGOs provide farmers with cost-sharing options to access expensive services such as machinery at a subsidised cost. Nevertheless, other types of support, including information and extension, are often complementary (Dakyaga et al., 2020).

6.4.4 Equitable distribution of agriculture resources and socioeconomic outcomes

Past literature has shown that household/community power dynamics, including gender, education, marriage and community, could deepen inequalities and affect the distribution of agriculture resources and livelihood outcomes needed to build a productive, resilient and efficient agriculture system. (Lawson et al., 2020; Nyantakyi-Frimpong, 2017).

Communities across RVB and BVB have diverse access to agriculture resources and livelihood outcomes relative to permanent water sources. The study findings have demonstrated that agriculture resources are more concentrated in communities with water sources for irrigation, depriving other communities of equitable resource access to build resilience against risks and increase crop productivity, especially in BVB. For instance, farmers in Mettow (BVB) tend to have access to access inputs (fertilisers and pesticides), extension services, and FBOs, which enable them to increase yields for food and market needs more than in Zambo/Yagturi. This finding aligns with previous research suggesting that farmers' access to dry season irrigation farming can increase productivity and enhance food security in SSA (MacCarthy et al., 2018; Schindler, 2009). Communities without irrigation opportunities tend to rely more on off-farm activities, especially in BVB. However, the Yagture (BVB) may be more vulnerable due to the limited on-farm and off-farm opportunities. The limited opportunities could trigger the overexploitation of ecosystem services through deforestation for commercial charcoal/firewood production.

Again, the study has shown that farmers' gender is more likely to determine agricultural resource access and livelihood outcomes, as men tend to access cropland, inputs and services than women, notably in BVB. For instance, cultural norms prevent women from owning cropland even though they may have access to smaller portions (< 2ha) than men. Women without ownership also lack control over croplands and could lose them through household conflicts or misunderstandings with the family head. Lack of cropland ownership creates land tenure insecurity, often hindering women from investing and maintaining the biophysical properties to increase productivity (Akugre, 2019). Surprisingly, women in both basins tend to migrate less and have fewer off-farm livelihood options and incomes, especially in BVB, where nearly half had no alternative livelihood opportunity. This finding contradicts numerous studies suggesting that women rather engage in alternative livelihood sources in Northern Ghana more than men (Lolig et al., 2014; A. L. Wood et al., 2021). The possible reasons for contradictory findings could be the focus of each study, where this study explored wider livelihood options, and previous studies looked at women-dominated options like petty trading.

Another critical finding from the study shows that marital status and household headship could determine access and distribution of resources and livelihood outcomes in both basins. Married farmers are more likely than unmarried ones to have access to extensive cropland for farming, especially in BVB, where about two-thirds of married farmers have more than two hectares of cropland. Married men, especially those with more considerable household sizes, increase cultivated areas for household food and market needs. These findings are no different from the earlier known knowledge in Northern Ghana, where household power dynamics in farm resource ownership favour married men (also household heads) in the community more than married/unmarried women (Akugre, 2019; Nyantakyi-Frimpong & Bezner-Kerr, 2015). To increase their household incomes, they tend to also engage in more livelihood diversification options than the unmarried ones in both basins. They may increase incomes to cover other household financial needs, including paying for health bills, children's educational needs, and purchasing extra food.

Educated farmers in both basins were more likely to access agriculture inputs like improved seeds, fertilisers, pesticides, and services such as information than less-educated ones. Educated farmers generate higher on-farm and off-farm incomes to increase yields to cater for other financial needs. For instance, educated farmers practice commercial farming and engage in paid labour through formal employment opportunities to increase farm expenditure for higher incomes and profits. On the contrary, less-educated farmers, especially women, are affected by unequal access to high-paying off-farm work, access to inputs (fertilisers, improved seeds, pesticides) and information services that enable farmers to enhance resilience, efficiency and productivity in both basins. Other studies have confirmed these findings by indicating that men or educated farmers have access to improved seeds due to higher incomes and social power than women or less-educated farmers (Ahmed et al., 2016; Dakyaga et al., 2020a; Nyantakyi-Frimpong & Bezner-Kerr, 2015).

Finally, the intersection between gender, education, household status and community suggests that less-educated women (married/unmarried) in communities without water sources are the most vulnerable social group, notably in the Yagture community in RVB with limited on-farm and off-farm outcomes. However, educated married men in communities with water sources could be considered the most resilient social group with favourable socioeconomic outcomes, especially for those in the Mettow community in BVB. Beyond the outcomes, the most vulnerable and resilient groups may interact differently with biophysical and socioeconomic characteristics, which may exacerbate risks or enhance productivity. Equitable distribution of resources among social groups, especially between gender, could enable vulnerable women farmers to access inputs and services that increase their resilience and productivity (Theriault et al., 2017).

6.4.5 Implication of socioeconomic characteristics and livelihood outcomes for SI in Northern Ghana

Key evidence from the present study will have implications for SI goals of productivity, resilience, efficiency and equity in RVB and BVB. On productivity, farmers with the potential to increase yields to meet household food needs were found to have access to dry season farming, participate in FBOs, access extension services and inputs, and increase farm investment. Pretty et al. (2011) assessed several SI projects across SSA and discovered similar findings suggesting that farmers with access to inputs and services enabled households to achieve the desired food needs. Even though these characteristics could enhance crop productivity under SI, they could become business-as-usual intensification actions with limited or no sustainability goals. Most smallholder farmers in semi-arid areas may prioritise intensification to meet household food needs rather than the sustainability needs of the agriculture system. Farmers' immediate needs may have short time rewards but long-term consequences, while sustainability needs may have incremental benefits for the agriculture system over time. The conflicting interest between farmers' production needs and sustainability goals poses a challenge for the SI in smallholder farming systems in West Africa. Some scholars have argued that not all sustainability goals can be achieved and that trade-offs are required to prioritise the agriculture system's needs to balance conflicting interests (Dakyaga et al., 2020b; Robinson et al., 2015b). Interventions focused on supporting households to make decisions, and set priorities for crop production could enable farmers to negotiate their food needs and sustainability goals under SI.

In addition, SI efficiency and resilience can be done through investment into effective strategies, exploring alternative livelihood options, and increasing access to information and services. The study has shown that farmers' who increase expenditure are more likely to increase on-farm strategies adoption and crop productivity outcomes in both basins. According to Aune et al. (2017), financial investments are required to adopt precision farming strategies like seed priming and micro-dosing, which have proven to build resilience and efficiency within some SI systems in West Africa. Unfortunately, due to cost-related challenges, cost-sharing opportunities could enable farmers access to services and strategies that could enhance efficiency and resilience. Public sector investments in agriculture could also enable strong national and local structures that provide farmers with the tools to cope with biophysical risks like climate change (Partey et al., 2018; Pretty et al., 2011).

Moreover, reducing over-dependence on crop production with migration and alternative livelihood options as off-farm activities could reduce the pressure on biophysical properties and enable resilient livelihood systems outside farming. However, activities like migration may not be an ideal off-farm option for increasing resilience under SI as the trade-offs between migration and active agriculture labour may not benefit the farming system in the long term. For instance, one result shows that farmers in communities in BVB with frequent migration tend to have lower yields and fewer alternative livelihood options. Supporting vocational skills like handicrafts making and food processing could expand the economic base and reduce the overreliance on farming, especially in BVB. The study's findings further show that agriculture services such as FBOs, information, education, and extension could enable the efficient use of available resources. As noted earlier, farmers may be more concerned about immediate food needs than prioritising efficiency; practical SI interventions may be required to increase awareness of balancing sustainability with productivity for long-term benefits.

Furthermore, equity in the present study's conceptual framing means all social groups involved in the crop production sector must benefit from SI outcomes with little to no losers. The findings have shown that less-educated women without irrigation or off-farm livelihood options are the most vulnerable, while educated men with irrigation and off-farm opportunities are the most resilient social group, notably in BVB. Struik and Kuyper (2017) have argued that the SI concept is about constant negotiations between social structures to find the perfect spot within the agriculture system where interventions and actions can benefit all social groups. Implementing SI without recognising the vulnerabilities and power dynamics within the agriculture system could result in some social groups being left out, further deepening inequalities between the most vulnerable and the resilient (Robinson et al., 2015b; Theriault et al., 2017). Vulnerable groups may migrate or overexploit ecosystem services with unsustainable activities like commercial charcoal, firewood or timber production from economic trees like shea. Theriault et al. (2017) assert that these compound vulnerabilities make it challenging for these social groups to be beneficiaries of SI interventions. However, the most resilient social group may intensify crop production and increase risks that may eventually affect the most vulnerable. Strategic dialogues to reconstruct sociocultural norms relating to tenure rights, inheritance and resource allocation could be the starting point for SI actions in Northern Ghana.

6.5 Practical Recommendations

6.5.1 Practice

To achieve higher productivity at the community level, SI implementation will require skills development on seed selection and improvements to withstand biophysical risks. However, controversies surround how far seed improvements significantly genetically modified organisms (GMOs) could go in SI practice, so there are no negative implications, including displacing indigenous varieties and affordability (Adenle et al., 2019; Dakyaga et al., 2020a). Raising local seed growers could resolve concerns about indigenous seeds and inputs affordability while addressing delays with the government's certified seeds. Productivity in SI would require continuous negotiations with traditional authorities on cultural barriers hindering women from accessing and having land tenure security for crop productivity. This action could increase farm investments and commitment to maintaining biophysical properties. Local institutions must support farmers with timely information, extension services and bookkeeping tools to track harvest trends for realistic yield expectations and enable suitable investments and inputs application for crop productivity, especially in BVB.

A resilient agriculture system will require local institutions to engage for-profit stakeholders like FBOs and out-growers to ensure intensification while minimizing biophysical risks by balancing profit/income and sustainability gains, especially in BVB. Alternatively, income and food source diversification, including animal rearing, aquaculture, and local manufacturing, could reduce the pressure on biophysical properties for optimum crop productivity. Strengthening local cooperatives and financing groups like the VSLAs could enable local-level financing to adopt strategies/technologies that enhance resilience.

Enhancing efficiency within the agriculture system will require the capacity to increase knowledge and skills through farmer schools, farm demonstrations and training programmes to help manage farm expenditure and input use to achieve resilience and productivity. Extension services, especially in BVB, need more AEA assistance from FBO leaders to reach vulnerable farmers, including women, the less-educated and those in communities without water sources. Innovations to introduce and expand communication channels to less-educated farmers could facilitate learning to enhance efficiency for resilience and productivity.

An equitable agriculture system could be established with local institutions supporting the most vulnerable groups, especially women with basic income/stipend and other livelihood diversification programmes such as soap making, shea butter processing, animal rearing and aquaculture. Community power structures, including Chiefs and opinion leaders, need to be engaged to ensure that vulnerable groups have equal access to resources regardless of education, marital status, and gender status.

6.5.2 Policy

Agriculture policy implementation for productivity, efficiency and resilience will require structures encouraging public-private partnerships for government programmes like PFJ to address input supply delays related to fertilizer and certified seeds. Policies incentivising agrochemicals and seed-producing companies to localize their production in parts of Northern Ghana could enable farmers' timely access to inputs for crop production. Further incentives, such as deregulating local financial institutions to support community financing models such as crop insurance schemes, cost-sharing programmes and low-interest credits/loans, could increase farm expenditure to adopt efficient on-farm strategies/technologies that enable resilience and productivity.

Also, national-level budgetary allocations for community water management systems, including dugouts, small dams and boreholes, could enable dry-season farming that reduces migration and boost productivity across RVB and BVB. Policy interventions that expand alternative livelihood sources for smallholder farmers, especially women, could prevent over-exploitation of biophysical resources for farming and reduce out-migration and poverty, especially in BVB. Procedures regarding forming FBOs need to be simplified to allow the existing social pool to become formalized. Alternatively, institutions like the DOA need to be resourced enough to assist farmers through the registration process for FBO formation. Instituting adult education programmes in the short-term and promoting general formal education could enable more educated farmers in the long term who may implement efficient strategies for resilience and a productive agriculture system.

Achieving an equitable distribution of resources will need local and national policy backing where the agency of vulnerable groups (unmarried and less-educated women) is enhanced to adopt efficient on-farm and off-farm strategies to enable agriculture system resilience and productivity, especially in communities without water sources in BVB. Policy engagement at the local level with institutions and traditional authority can enable negotiations around cultural norms like inheritance structures to allow women the opportunity to inherit croplands in RVB and BVB.

6.5.3 Research

Due to its limited scope, the present study did not conduct a detailed agriculture profitability assessment. Future studies could focus on assessing yield profitability in the context of yields/ha consumed and sold to reflect the economic benefits of crop production in RVB and BVB. Longitudinal studies will also be needed to study household yields/ha trends and behavioural dynamics that could predict changes in productivity outcomes. Future research could investigate how agricultural inputs and services distribution among vulnerable social groups reduces crop expected and actual yields/ha in RVB.

6.6 Summary

This objective aimed to assess and compare socioeconomic determinants of productivity and livelihood outcomes that could enable or hinder SI goals in RVB and BVB of semi-arid Northern Ghana, according to the aim of Objective 2. The results and analysis from the survey showed that most respondents in both basins depend on subsidised certified seeds, especially maize, from the government PFJ programme for cultivation. However, frequent delays and a limited supply of certified seeds force farmers to rely on input retailers (in BVB) and family/friends (in RVB).

Even though expected yields among respondents are similar, the actual yield for the essential crops differ depending on access to water sources, gender, education, FBOs, extension services, investment/expenditure, inputs and services. The findings revealed that farmers in RVB are more subsistence-based with food crops (cereals) production, while those in BVB are more commercially oriented with groundnut production. These crop production differences may be due to the larger household size and population density in RVB, which may demand more food crops. Married men who are household heads and reside within communities with water sources are the most productive social group with higher socioeconomic outcomes like access to capital and inputs, while unmarried and less-educated women without water sources are the least productive, especially in BVB. Revenues raised from off-farm activities, loans and savings enabled farmers in both basins to increase farm investments, increasing crop yields and yield incomes. Communities in RVB with lower crop yields and incomes have high off-farm options and revenues, while those in BVB with lower crop yields have the least off-farm options and revenues, making them the most vulnerable farmer group between the two basins. However, farmers in BVB tend to receive remittances to supplement low alternative livelihood incomes.

These findings imply that socioeconomic characteristics, including education, gender, FBO membership, extension services, off-farm activities (alternative livelihood and migration), capital investment (loans, savings and credit), inputs (fertilizers, improved seeds and pesticides) and services (information, extension and machinery) could enhance or hinder crop productivity, resilience, efficiency and equity for SI in RVB and BVB. Achieving SI goals will require national policy backing to implement interventions around agriculture incentives, subsidies, extension, funding and education through institutional collaborations and community engagements. These policies and interventions can reduce the socioeconomic vulnerabilities among the identified groups while supporting productive farmers to use agriculture resources sustainably. The next chapter examines the institutional constraints that could hinder and the entry points that could enable SI goals to be achieved in RVB and BVB.

CHAPTER 7

INSTITUTIONAL CONSTRAINTS AND ENTRY POINTS FOR AGRICULTURE INNOVATION IN SEMI-ARID GHANA

7.1 Introduction

This PhD aims to determine the factors contributing to productivity differences between RVB and BVB and how these factors could influence the implementation of SI within smallholder agriculture systems in semi-arid Northern Ghana. The study's objectives are to assess and compare the biophysical, socioeconomic and institutional characteristics of the smallholder agriculture system that could hinder or enable SI in Northern Ghana. This chapter compares institutional constraints and entry points for implementing SI in semi-arid RVB and BVB. The chapter answers these broader questions: *i)* What institutional characteristics (constraints and entry points) within semi-arid Northern Ghana could hinder or enable agriculture innovation in RVB and BVB? and *ii)* What implications will institutional constraints and entry points have on achieving SI in RVB and BVB?

The Rapid Appraisal of Agricultural Innovation Systems (RAAIS) participatory approach is adopted to examine institutional constraints and entry points for SI in RVB and BVB. The approach includes workshops, KII, FDGs and some survey information with institutional stakeholders. Five stakeholders from five formal and informal local institutions participated in the study, including FBO leaders, AEAs, community leaders (Traditional authority/opinion leaders), input retailers/suppliers, and NGO practitioners. See ***Appendix A (iv)*** for details.

The chapter covers the following sections: **7.2** presents the results of institutional constraints and entry for farm innovation; **7.3** analyses examine the similarities, differences and relationships between institutional constraints between RVB and BVB; **7.4** discusses the findings alongside previous studies in Northern Ghana and their implications for SI; **7.5** looks at the practical recommendation for SI in Northern Ghana/West Africa based on the findings; **7.6** summaries the chapter.

7.2 Results: Institutional constraints and entry points for innovation

7.2.1 Institutional constraints to agriculture innovation

This section presents the results on institutional constraints/barriers to implementing innovative agriculture strategies in RVB and BVB. After identifying these constraints and their dimensions, stakeholders were also asked to point out entry points and propose solutions for implementing SI in both basins. Stakeholders identified constraints related to their own institutions and categorised them under four dimensions: *(1) institutional subsystem* – categories within institutions, *(2) governance* – actions/processes to govern the agriculture system, *(3) administrative levels* – management of affairs within the agriculture system *and (4) structural conditions* – the settings that make the agriculture system functions.

7.2.1.1 Institutional constraints identified by stakeholders

To identify the relevant constraints, each stakeholder group developed their top 5 constraints that could hinder the implementation of new/innovative strategies to achieve SI goals in the RVB and BVB agriculture systems. Overall, 25 institutional constraints were identified in each basin, shown in **Table 54** below. These constraints may manifest in more than one constraint category and dimension.

Table 54: *Comparing institutional/stakeholder constraints that could hinder agriculture innovation between RVB and BVB. Source: Fieldwork, 2021.*

Groups	Basin	Stakeholder constraints				
		One	*Two*	*Three*	*Four*	*Five*
Farmers (FBO leaders)	*RVB*	Inadequate tractor services	Delay in inputs supply (e.g., Seeds & fertilisers)	Poor market	Inadequate improved seeds	Unreliable rainfall
	BVB	Inadequate tractor services	Delay in inputs supply (e.g., Seeds & fertilisers)	Low market prices	The high cost of input	Pest infestation (field & storage)
Extension Agents	*RVB*	Low soil fertility	Delay in inputs	Poor road network	Inadequate irrigation activities	Inadequate logistics
	BVB	Language barrier	Poor service conditions	Belief systems among farmers	Lack of farmer trust for extension services	Inadequate logistics
Community Leaders	*RVB*	Poor inputs use (e.g., pesticide & fertiliser)	Inadequate farm inputs and services	Conflict over resources	Poor timing of input supply	Pest and disease infestation
	BVB	Land and soil degradation (bushfires & charcoal production)	Absenteeism and irregular community meetings	Inadequate community sensitisation	Inadequate resources to support agriculture	Low capacity among community leaders
Input Suppliers	*RVB*	Lack of access to credit	Poor inputs use (e.g., pesticide and fertiliser)	Poor road network	Unfavourable government policies towards input supply	Challenges with the use of new technologies
	BVB	Non-payment of credit on inputs	High-interest rate on inputs	Inadequate irrigation activities	Unfavourable government policies towards input supply	Poor sales of inputs
NGOs	*RVB*	Low adoption rate	High illiteracy rate	The late release of project funds	Unreliable or erratic rainfall	Limited access to farm inputs and services
	BVB	Low extension-to-farmer ratio	Poor knowledge transfer among	Unsustainable agriculture projects	The high cost of farm inputs	Lack of funds for the local/community project

7.2.1.2 Constraints under institutional subsystems

Stakeholders were presented with six institutional subsystems to categorise their constraints under them in RVB and BVB. These subsystems include policy, research, education/training, extension, markets, and politics, as shown in **Figure 40** below.

About 52% of constraints are policy-related, especially for NGOs in BVB, AEAs in RVB and input suppliers in both basins. These results could be due to unfavourable government policies towards input supply and less resource allocation for AEAs and NGOs in RVB and BVB compared to the rest of the country. Research-related constraints were more in RVB (20%) than in BVB (4%), especially for FBOs. However, education/training-related constraints are more for AEAs and community leaders in BVB (24%) than for NGOs in RVB (8%).

These results indicate how inadequate education/training hinders NGOs, community leaders and AEAs from accessing information/knowledge to implement efficient strategies needed to boost agriculture, especially in BVB. FBO constraints are related mainly to policy, research and market systems due to their total dependence on these dimensions.

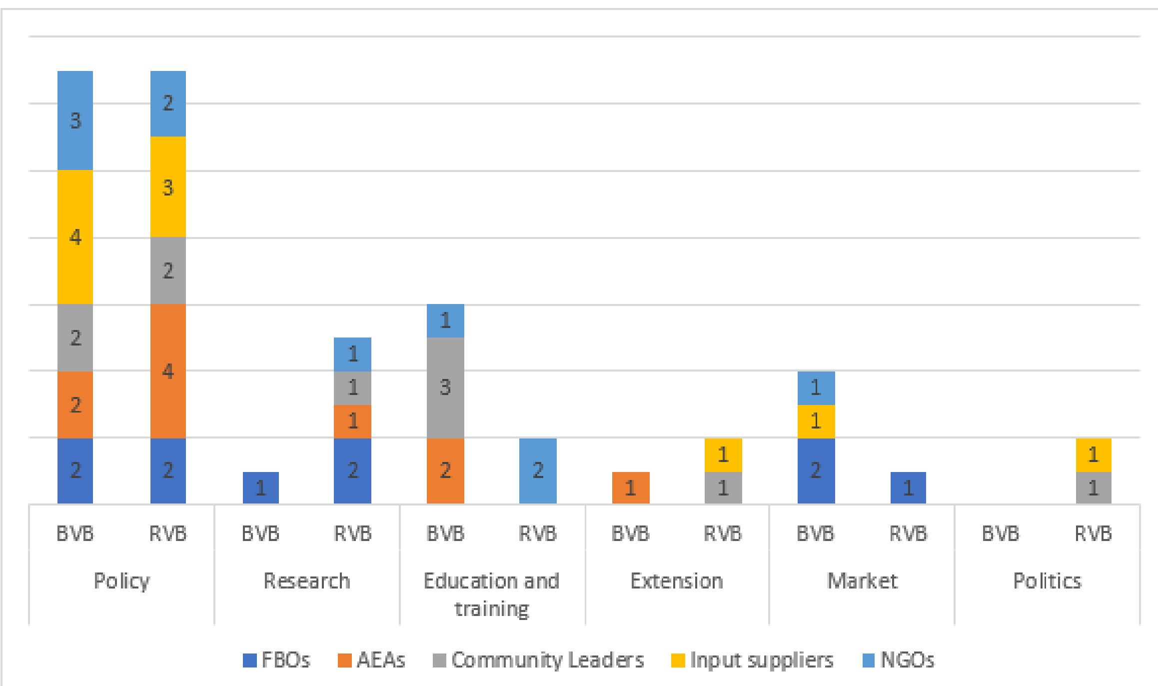

***Figure 40**: A Stacked bar chart comparing the number of constraints under the institutional subsystems between RVB and BVB*

7.2.1.3 Constraints under governance dimensions

Stakeholders were presented with five governance dimensions (Kaufmann et al., 2011) to categorise their constraints under them in RVB and BVB. These dimensions include accountability, stability, effectiveness, the rule of law and corruption, as shown in **Figure 41** below.

About 48% of constraints in RVB are related to effectiveness, primarily within NGOs, input suppliers and community leaders. 56% of constraints in BVB are accountability and effectiveness related, mainly for NGOs. This outcome may be due to a lack of effectiveness and accountability in policy implementation, such as delays, poor timing, or late delivery of subsidised inputs to farmers.

About one-fifth of constraints in both basins are stability-related, especially for FBOs and AEAs. During the workshop discussions, FBO and AEA groups mentioned that more of their constraints resulted from environmental and social instability, such as erratic rainfall, deficient soils, poor road networks and an unstable market system.

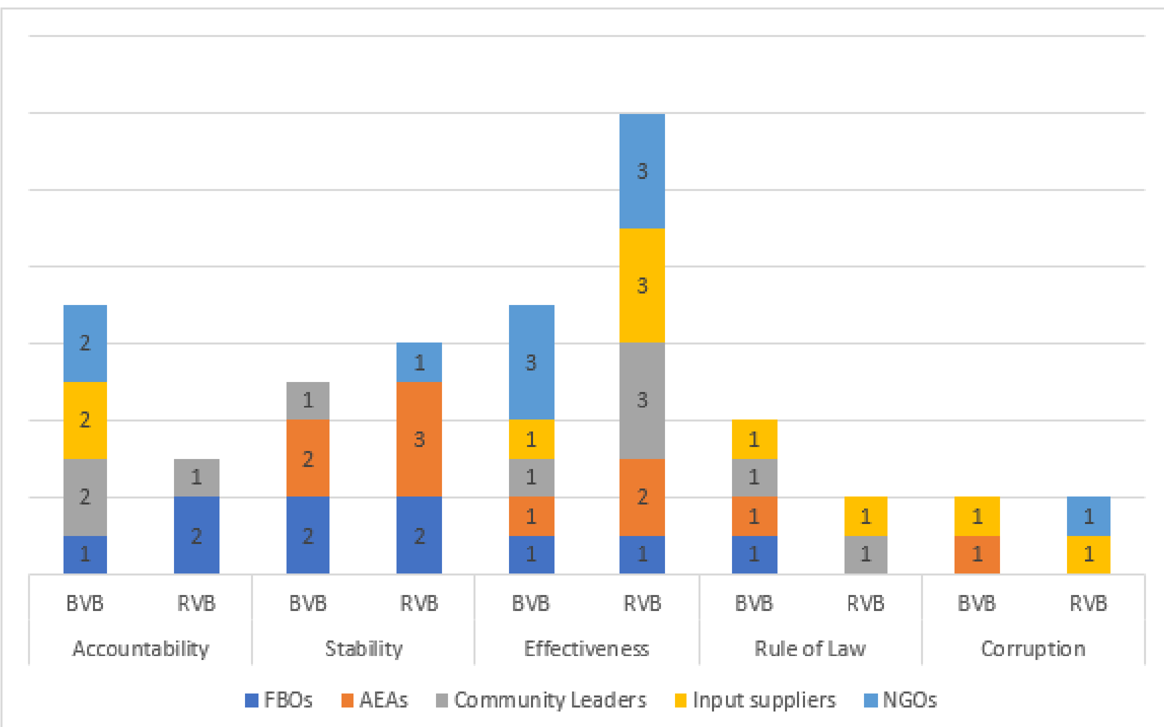

***Figure 41**: A Stacked chart comparing the number of stakeholders' constraints under the 5 governance dimensions between RVB and BVB*

7.2.1.4 Constraints under administrative dimensions

Stakeholders were presented with four administrative levels to categorise their constraints under them in RVB and BVB. These levels include national, regional, district, and local/community, as shown in **Figure 42** below.

More constraints were categorised under national and community levels in both basins. Constraints under the national level are more in BVB (40%) than RVB (32%), while those under the community level are more in RVB (40%) than BVB (32%). This result may be due to the decentralised governance structure in Ghana, where national institutions enact agriculture policies and local institutions implement those policies. For instance, institutions (NGOs in BVB and AEAs in RVB) depend on national-level resources, including logistics and funding for local-level implementation. 60% of input suppliers' constraints in BVB are under the national level due to their dependency on the national input supply for distribution at the community level.

Again, FBO constraints cut across national, regional, and district levels in both basins, possibly due to farmers' dependency on all institutions across the administrative spectrum to support farming at the community level. Community leaders perceive many constraints at community and district levels due to their role in supporting farmers locally.

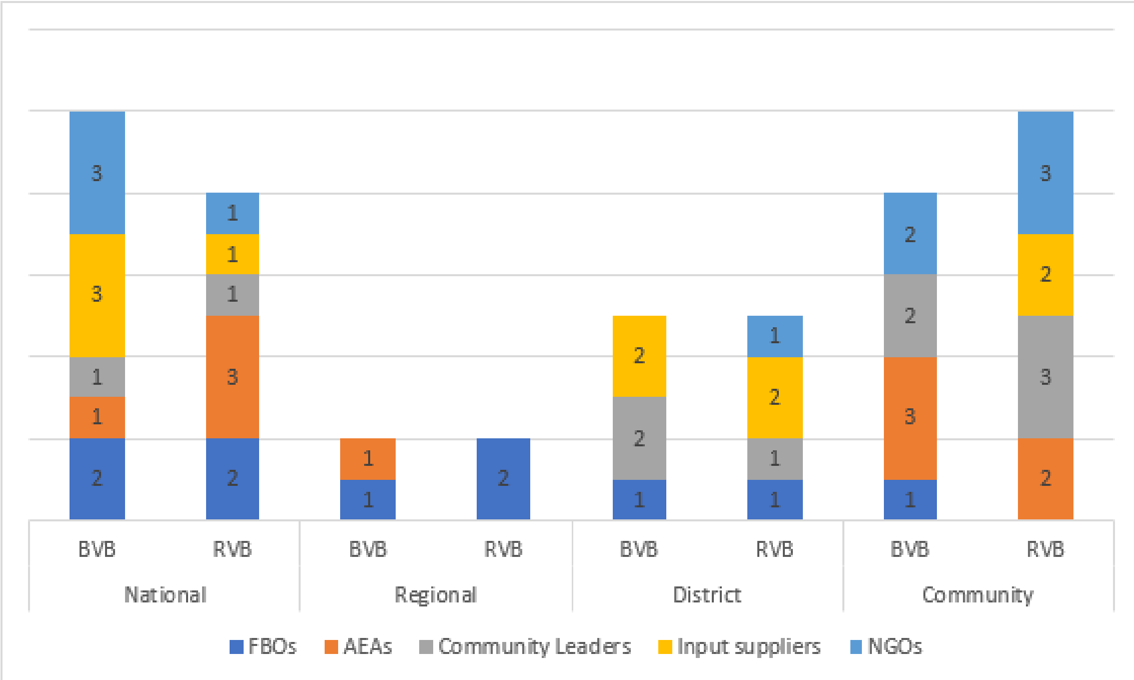

***Figure 42**: A stacked bar comparing the number of stakeholders' constraints under four administrative levels between RVB and BVB*

7.2.1.5 Constraints under structural conditions

Stakeholders were presented with four structural conditions to categorise their constraints under them in RVB and BVB. These conditions include infrastructure/assets, institutions, interactions/collaborations, and capacities, as shown in **Figure 43** below.

About 60% of constraints in both basins were categorised under institutions and poor interaction/collaboration. Inadequate collaboration and interaction among institutions hinder knowledge/information exchange that could facilitate the implementation of innovative agriculture strategies.

FBO constraints were categorised under all structural conditions in both basins, possibly due to their dependency on these structures for crop production. However, 25% of constraints in both basins were related to inadequate capacities (on biophysical risks management), especially for NGOs.

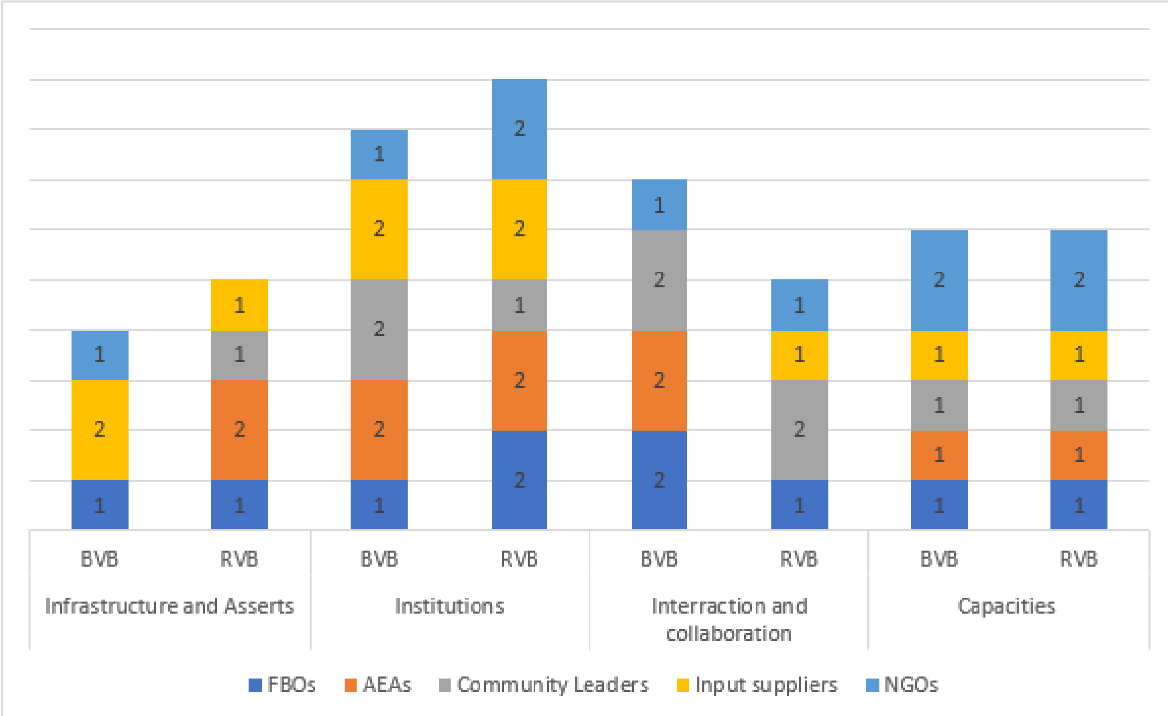

Figure 43: *A stacked bar chart comparing the number of stakeholder constraints under four structural conditions in RVB and BVB.*

In summary, most constraints that could hinder agriculture innovation in both basins were issues related to policy and effectiveness within institutions and polarised at the national and local levels.

7.2.2 Exploring potential entry points for SI

This section explores entry points for the potential implementation of SI within RVB and BVB. Stakeholders categorised constraints under three entry points: *i) internal or collaborative solutions, ii) difficult or easy solutions, and iii) generic or specific solutions.*

7.2.2.1 Solving constraints internally or collaboratively

Stakeholders categorised constraints according to how they could be addressed, including internal (within institutions) or collaborative (institutional partnerships) solutions in RVB and BVB, as shown in **Figure 44** below.

Institutional collaboration can address more constraints in RVB (80%) than in BVB (64%). However, internal solutions could address more constraints in BVB (36%) than in RVB (20%). Even though overwhelming constraints could be addressed through partnerships, the stakeholder groups (except FBOs) believe internal resources/capacity could address some constraints in RVB and BVB. FBOs in both basins believe all constraints should be addressed in collaboration with other institutions. As noted earlier, farmers in both basins are over-dependent on local institutions for resources, believing they are not responsible for internally addressing some constraints.

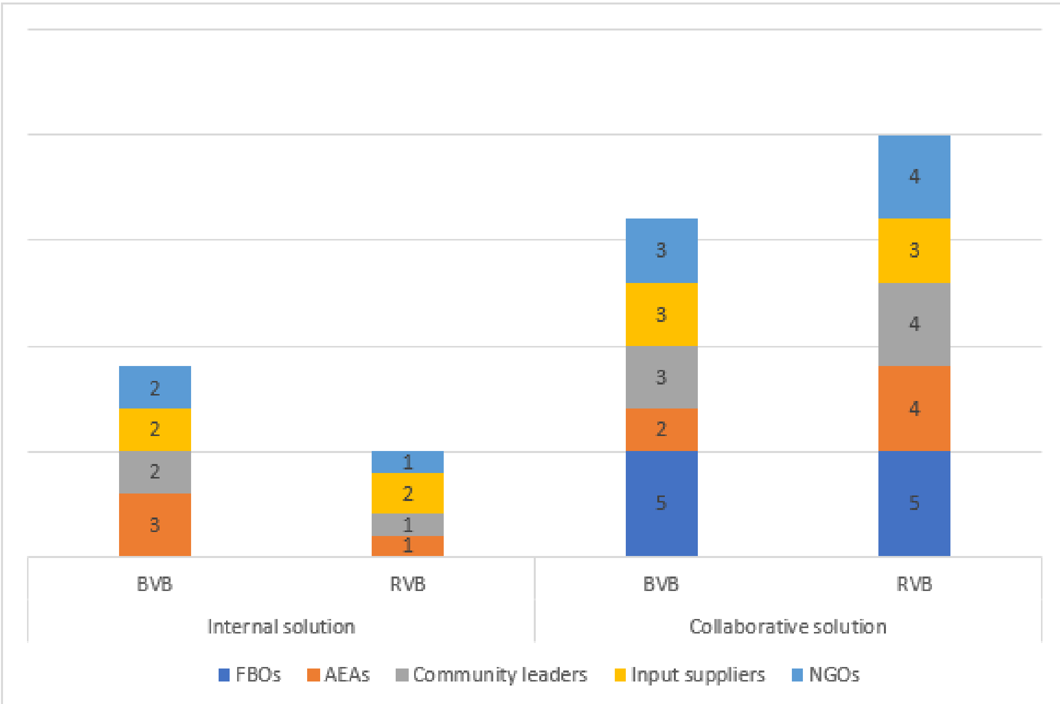

***Figure 44**: A chart showing the number of constraints stakeholders can solve internally or collaboratively in the RVB and BVB.*

7.2.2.2 Constraints with easy or difficult solutions

Even though stakeholders may solve some constraints internally and others through collaboration, some may be more complex than others. Stakeholders identified constraints that require system optimisation (easy to solve) or transformation (complex/difficult to solve) in RVB and BVB, as shown in **Figure 45** below.

More constraints in RVB (72%) than in BVB (40%) were considered easy to solve. FBOs, AEAs, input suppliers, and community leaders in RVB believe that constraints could be easier to solve when available resources are optimised. However, more constraints in BVB (60%) than in RVB (28%) were identified as difficult to solve by FBOs, AEAs, input suppliers, and community leaders.

Furthermore, NGOs in both basins believe their constraints may be complex to solve, especially regarding funding. During the workshop discussions, NGO groups indicated that funding has been difficult as donors often prefer working with local government institutions to local NGOs, making staff recruitment and logistics for community work challenging.

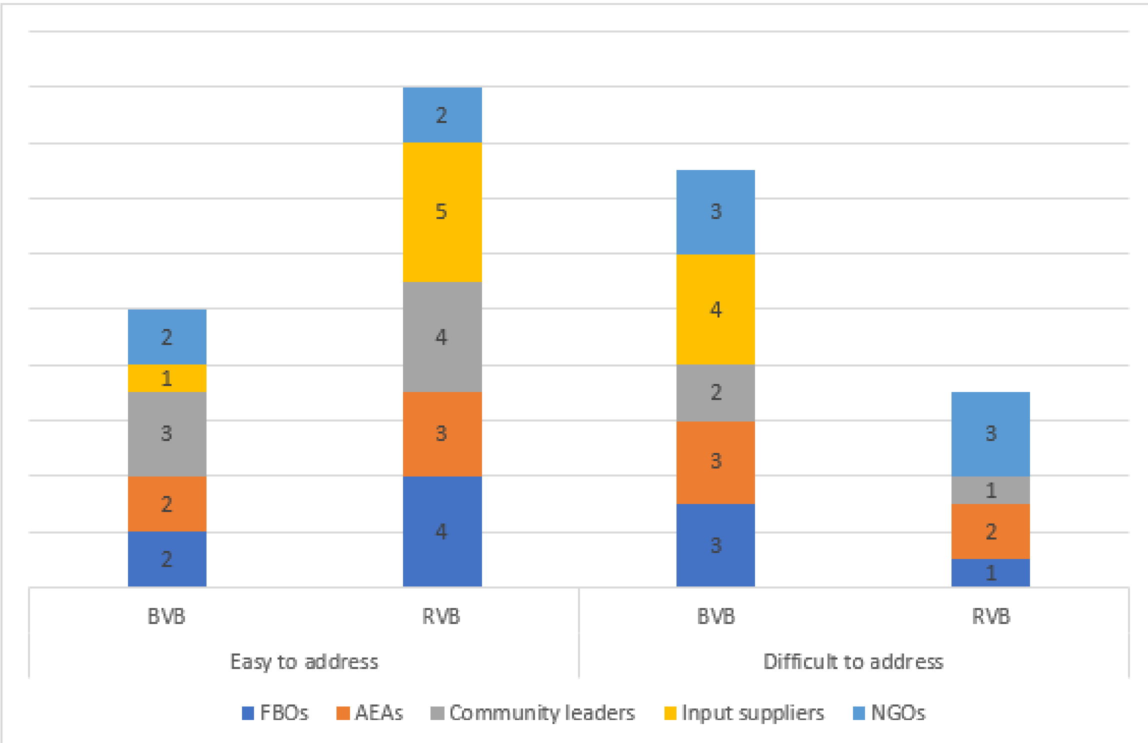

***Figure 45**: A bar chart comparing the number of constraints that require easy or difficult solutions in RVB and BVB.*

7.2.2.3 Constraints requiring generic or specific solutions

Stakeholders categorised constraints under the 4-step gradients*: "very structural", "structural", "very operational", and "operational"*, as shown in **Figure 46** below.

Structural constraints affect the organisational structure of an institution, while operational constraints affect the day-to-day activities within an institution. "Very structural" emphasises a high degree of structural constraints, while "very operational" emphasises a high degree of operational constraints. Constraints classified under *"very structural"* or *"very operational"* may require specific strategies, while those under *"structural"* or *"operational"* constraints require generic strategies.

Stakeholders in BVB perceived more of their constraints as "*structural*", while those in RVB tend to perceive them as *"very structural"*. FBOs and input suppliers in BVB perceived most of their constraints as *"structural"*, requiring generic interventions as solutions. However, AEAs in RVB perceived 60% of their constraints as *"very structural"*, requiring specific interventions as solutions.

Also, stakeholders from FBO groups in both basins perceived 60% of their constraints as *"structural"* barriers that require implementing generic strategies as solutions. Community leaders in RVB perceived 60% of their constraints as *"very operational"*, requiring specific solutions.

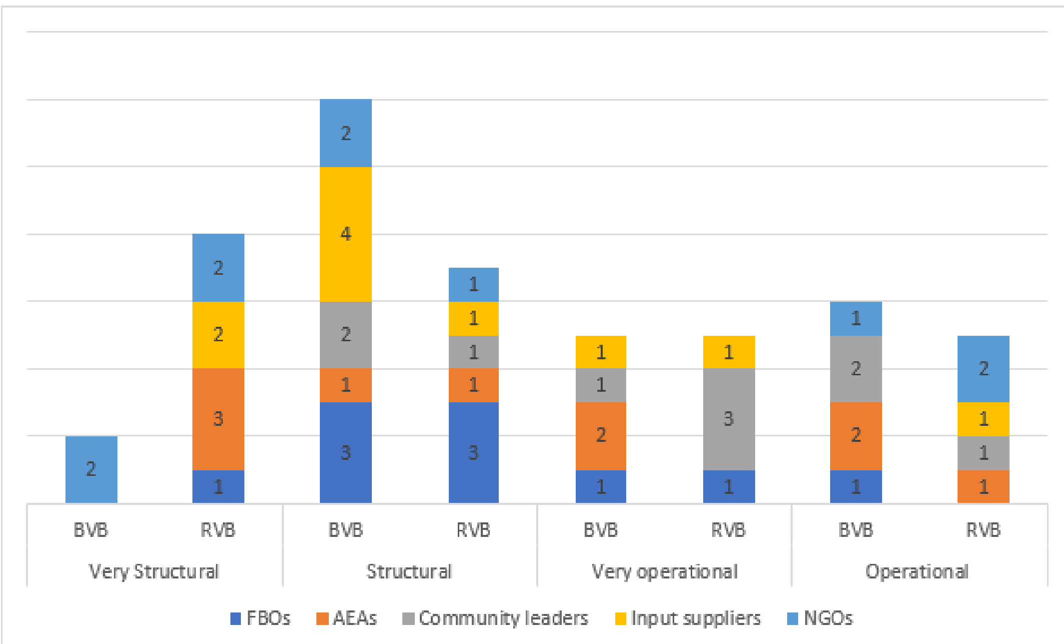

Figure 46: *A Stacked bar chart comparing the number of constraints under the 4-step gradient between BVB and RVB.*

In summary, most constraints could be addressed through institutional collaboration in both basins. However, most constraints in RVB could be easy to address with specific strategies, while most constraints in BVB could be difficult to address and may require generic strategies.

7.3 Analysis: Similarities, differences and relationships between constraints and entry points

This section examines the similarities, differences and relationships between institutional constraints to identify the most critical ones in RVB and BVB. SI entry points are analysed through cross-tabulation between critical constraints and solutions in both basins.

7.3.1 Similarities and differences between constraints

7.3.1.1 Constraints similarities and differences across institutions

Constraint similarities and differences were identified within each institution/stakeholder group between RVB and BVB.

The analysis showed that constraint similarities between RVB and BVB were 60% within FBOs, 40% within Input suppliers and NGOs, and 20% within AEAs and Community leaders.

Constraints similarities between FBOs in RVB and BVB include input delays, inadequate tractor/machinery services, and poor market. Even though farmers with FBOs are more likely to acquire subsidised PFJ inputs (fertilisers and certified seeds), delays in supply hinder access, forcing farmers to purchase from input suppliers at a higher price. An FBO leader in a KII explained that input delays often affect cropping times, expenditure and farm size:

> *"One of the major challenges we face is fertilisers and chemicals delays from DOA for the farming season. By the time we get access to these subsidies, the planting season is about 3 to 4 weeks in, forcing us to rely on few expensive inputs from retail shops and reduce our farmland size."*
>
> *- FBO leader, Zambo Community in BVB.*

Also, farmers struggle with tractor services for land preparation in RVB and BVB, especially women farmers without the capital to hire one. Crop production from nearby communities in Burkina Faso with enhanced irrigation farming creates market competition for commercial farmers in both basins.

For input suppliers, unfavourable government policy on PFJ input supply and inadequate credit facilities to access inputs were the similarities between RVB and BVB. From the survey, a few respondents in RVB (17%) and BVB (10%) could access credit for farming. In a KII (RVB), an input supplier explained that most farmers are without collateral to access credit/loans for inputs, and those who could access credit/loans are often unable to repay, making it a disincentive to offer them to farmers.

NGO groups' constraint similarities between RVB and BVB were related to unsustainable project funding and input cost/access. Development partners often provide funding to local NGOs for limited periods, making it challenging to sustain projects. An NGO practitioner explained that some constraints require long-term commitment with adequate funding to address, especially those that need agriculture system transformation.

> *"Most often, our development partners we work with demand short-term results from activities that need long-term implementation. Therefore, due to short-term funding, most projects do not produce sustainable long-term outcomes."*
>
> - *NGO Practitioner in RVB*

NGOs usually support farmers when subsidised PFJ inputs are delayed and must purchase at high prices from input suppliers to support farmers.

Moreover, inadequate transportation, personnel, and field logistics are similar constraints typical for AEAs in both basins. Most AEAs lack transportation means for field visits, relying on personal transportation for fieldwork. The low AEA-to-farmer ratio puts enormous pressure on a few AEAs to support thousands of farmers in different communities. Protective gear, navigation tools, and communication devices are inadequate for effective field operations in both basins. An AEA in BVB mentioned that the AEA turnover rate is high due to challenging work conditions.

> *"Working as an AEA in this region is very challenging. Few field officers serve many farmers in different communities with minimal resources. We receive little remuneration at the end of the month that cannot support our families. This situation has pushed many colleagues to seek better job offers elsewhere".*
>
> - *AEA, DOA-Lawra*

For community leaders, inadequate resources, including farm inputs, information and capital to support farmers in their communities, are the similarities between RVB and BVB. Community leaders are responsible for developing communities, and to that end, supporting major livelihoods like farming is essential. However, inadequate capacity to share information on environmental change, including degrading soils, erratic rainfall, water pollution and bushfires, often makes it challenging to support farmers who look up to them for solutions. Some vulnerable farmers look up to community leaders for financial support, as emphasised by a community Chief in RVB.

"At the beginning of each farming season, vulnerable farmers like widows, single mothers and disabled farmers come to the palace for seeds, fertilisers and financial support to prepare their land. I often have to send some people away due to limited resources."

- *Chief of Lungu Community, RVB*

Table 55*: Comparing constraints that differ among stakeholder groups between RVB and BVB. (Source: Fieldwork, 2021).*

Stakeholder Group	RVB	BVB
FBOs	• Pest infestation (field & storage) • The high cost of input	• Inadequate information strategies • Unreliable rainfall
Extension service	• Language barrier • Poor service conditions • Belief systems among farmers • Lack of farmer trust for extension services	• Low soil fertility • Delay in inputs • Poor road network • Inadequate irrigation activities
Community leadership	• Poor inputs use (e.g. Pesticide & fertilizer) • Conflict over resources • Poor timing of input supply • Pest and disease infestation	• Land and soil degradation (bushfires and charcoal production) • Absenteeism and irregular community meetings • Inadequate community sensitization • Low capacity among community leaders
Input suppliers	• Poor inputs use (e.g. Pesticide and fertilizer) • Poor road network • Challenges with the use of new technologies	• High-interest rate on inputs • Inadequate irrigation activities • Poor sales of inputs
NGOs	• Low adoption rate • High illiteracy rate • Unreliable or erratic rainfall	• Low extension to farm ratio • Poor knowledge transfer among • Unsustainable agriculture projects

7.3.1.2 Relationships between constraints

The participatory process enabled stakeholders to indicate the critical/top constraints by identifying relationships to establish entry points for SI within RVB and BVB. All stakeholders within each basin grouped constraints into clusters (top/critical constraints) and their relationships, as shown in **Table 56** below. Clusters are the number of constraints with similar characteristics, while relationships are the network of constraints related to a cluster. See **Table 57** below as an example of cluster and relationship and ***Appendix I*** for more details.

Table 56: *Comparing constraints clusters and nodes between BVB and RVB. (Source: Fieldwork, 2021).*

No.	Clustered/Critical/Top constraints	No. of constraints		No. of relationship	
		BV	RV	BV	RV
1	Policy (input supply & delivery)	6	5	17	13
2	Resources (education, inputs, services, finance)	5	6	16	17
3	Community meetings/engagement	2	-	7	-
4	Cost (inputs and services)	4	-	6	-
5	Information & Knowledge	4	5	9	12
6	Natural resources (soil/rain/pest)	-	4	-	12
7	Others (road, conflicts)	3	4	5	4
	Total	***25***	***25***		

Table 57: *Showing the cluster and relationships for information and knowledge in BVB.*

Information and knowledge Cluster	Relationships
1) Belief systems among farmers *2) Poor knowledge transfer* *3) Lack of farmer trust in extension services* 4) *Inadequate community sensitisation*	1) Unsustainable agriculture projects 2) Land and soil degradation (bushfires & charcoal production) 3) Delay in inputs supply (e.g., Seeds & fertilisers) 4) Pest infestation (field & storage) 5) Language barrier 6) Low capacity among community leaders 7) Absenteeism and irregular community meetings 8) Inadequate irrigation activities 9) Lack of funds for the local/community project

Stakeholders in BVB identified 5 critical/cluster constraints related to policy, resources, community meetings, cost and information/knowledge, while those in RVB identified 4 critical/cluster constraints related to policy, resources, information and natural resources. Constraint clusters related to policy (on input supply and delivery), resources (education, inputs, services and finance), and information/knowledge were similar between RVB and BVB. However, community engagement and input/services costs are unique cluster constraints to BVB, while natural resources (poor soils, erratic rainfall and pests) are unique to RVB. Other constraints, such as poor roads and conflicts, have fewer relationships in both basins.

Policy and resource-related constraint clusters and their relationships are related to inputs supply and delivery in RVB and BVB. Cost, regular supply, subsidies, credit facilities, AEA logistics, irrigation tools, and land are the inputs related to agriculture policies and resources that define productivity in both basins. However, input policy and resource constraints affect all local institutions as their work overlaps with each other within the agriculture system. For instance, community leaders engage with AEAs and NGOs to make subsidised inputs available to farmers, while input suppliers provide additional inputs throughout the farming season.

Furthermore, community engagement and information/knowledge in BVB are related to inadequate empowerment and capacity for institutions. Community leaders are responsible for mobilising farmers for AEAs and NGO training or information dissemination events. In RVB, these training and information dissemination events are usually on natural resource management, including soil, water and ecosystem management.

In general, policy, resource access and information/knowledge-related challenges could hinder SI actions in both basins. However, specific attention should be given to constraints related to community engagements in BVB and the cost of inputs/services in RVB for effective implementation of SI.

7.3.2 Entry points for addressing stakeholder/institutional constraints

This section analyses the pathways to addressing clustered/critical constraints to achieve SI goals in RVB and BVB. Cross-tabulation is used to identify how easy or difficult it is to solve critical constraints, whether the solutions require internal or collaborative efforts and which generic or specific strategies are needed to resolve these constraints.

7.3.2.1 How easy or difficult to address critical constraints

Critical constraints were triangulated with how easily (or difficult) they could be addressed in RVB and BVB. **Table 58** below shows that more constraints in RVB related to policy, access to resources and knowledge/information transfer could be easy to address. On the contrary, more constraints in RVB related to policy, resources and community engagement were considered difficult to address. The possible reason for this outcome could be that stakeholders in RVB consider more constraints as local administrative level constraints, while those in BVB consider them national level constraints. Bureaucratic structure at the national level makes it difficult to resolve constraints, whereas local structures are less bureaucratic, making constraints easier to address. With system optimisation, stakeholders in RVB could address most of their institutional constraints, while those in BVB will require system transformation to address most of their constraints.

Furthermore, stakeholders in BVB perceive that those constraints related to community engagements could be both easy or difficult to solve. This outcome could be that stakeholders, especially community leaders, NGOs and AEAs, can easily address community meeting absenteeism with proper incentives, even though language barriers or cultural beliefs could be difficult to resolve. For RVB, constraints related to natural resources, such as erratic rainfall and droughts, may be difficult to address, as they believe that climate change-related constraints require national and international efforts to resolve.

> *"The changing climate is affecting the timing and intensity of rainfall. For some time now, it does not rain as expected. When it does, it is intense over a short period. This situation disrupts our farming activities, and we need the government or some international organisation to help resolve this."*
>
> *- FBO leader, RVB*

Table 58*: The distribution of key constraints that are classified as easy/difficult to solve for both the Black and RVB*

No.	Clustered constraints	Easy to solve		Difficult to solve	
		BVB	*RVB*	*BVB*	*RVB*
1	Policies (input supply & delivery)	2 (34%)	4 (80%)	4 (66%)	1(20%)
2	Resources (education, inputs, services, finance)	1 (20%)	4 (57%)	4 (80%)	3 (43%)
3	Community engagement	2 (50%)	-	2 (50%)	-
4	Cost (inputs and services)	2 (100%)	-	-	-
5	Information (Knowledge transfer)	3 (75%)	5 (100%)	1 (25%)	-
6	Natural resources (soil/rain/pest)	-	1 (25%)	-	3 (75%)

7.3.2.2 How institutions can address easy or difficult constraints

Easy or difficult constraints solutions are triangulated with constraints that could be addressed internally or collaboratively. The outcome shows that more constraints in RVB than BVB considered "*easy to solve"* could be done through institutional collaboration, as shown in **Table 59** below. However, more constraints in BVB than RVB that are considered "*difficult to solve"* could also be done through institutional collaboration.

Moreover, *"easy to solve"* constraints that could be addressed internally are similar between both basins. However, while a few constraints were considered *"difficult to solve"* internally in BVB, stakeholders in RVB could not identify any internal constraints as "*difficult to solve"*. These results suggest collaboration is an essential strategy to resolve the most challenging institutional constraints in RVB and BVB. Collaborations allow stakeholders to rely on the strength (capacities and resources) of each other to support themselves and farmers.

Table 59*: A cross-tabulation comparing constraints considered easy or difficult to solve internally or through collaboration between RVB and BVB. (Source: Fieldwork, 2021).*

	Solved within (Internal)		**Solved with others (collaborative)**	
	BVB	*RVB*	*BVB*	*RVB*
Easy to solve	6 (24%)	5 (20%)	4 (16%)	13 (52%)
Difficult to solve	3 (12%)	0 (0%)	12 (48%)	7 (28%)

7.3.2.3 How 4-step gradient can address easy or difficult critical constraints

Easy or difficult constraints are triangulated with the 4-step gradient *("very structural", "structural", "very operational", and "operational")* to identify which easy or difficult constraints need generic or specific strategies to solve in RVB and BVB, as shown in **Table 60** and **Table 61** below.

Table 60*: Critical constraints under the 4-step gradient and how easy or difficult they are to solve in BVB. (Source: Fieldwork, 2021).*

4-step gradient	**Easy to solve**	**Difficult to solve**
Very Structural		• ***Resources*** (lack of project funds, the low extension to farmer ratio)
Structural	• ***Policy*** (Unsustainable projects) • ***Resources*** (insufficient tractor services)	• ***Policy*** (High-interest rate, policy on input supply, delay in input supply) • ***Cost of input*** • ***Resources*** (Low capacity by community leaders, Educational & financial resources, Inadequate logistics)
Very Operational	• ***Information & knowledge*** (low education on environmental challenges) • ***Cost of input*** (Non-payment of input purchase) • ***Policy*** (Poor service conditions)	• ***Information & knowledge*** (Belief systems among farmers)
Operational	• ***Information & Knowledge*** (Language & communication barriers, Poor knowledge transfer) • **Community engagement** (Land and soil degradation, absenteeism at community meetings) • ***Cost of input*** (low farmer inputs purchasing power)	• ***Information & knowledge*** (Lack of farmer trust for extension services)

Table 61*: Critical constraints under the 4-step gradient and how easy or difficult they are to solve in RVB. (Source: Fieldwork, 2021).*

4-step gradient	Easy to solve	Difficult to solve
Very Structural	• ***Policy*** (gov't policy on input supply)	• ***Resources*** (late release of project funds, limited access to inputs/services) • ***Natural resources*** (climate change/erratic rainfall)
Structural	• **Resources** (inadequate tractor services, farm inputs - improved seeds, fertilizers)	• ***Resources*** (Inadequate field equipment)
Very Operational	• ***Information & knowledge*** (low education on environmental challenges and input use) • ***Policy*** (late delivery of inputs)	
Operational	• ***Information & knowledge*** (High illiteracy, low adoption rate) • **Natural Resources** (Low soil fertility) • ***Cost of input*** (lack of access to credit)	• ***Natural Resources*** (Pest and disease infestation)

Information/knowledge-related constraints in both basins are mainly *"easy to solve"* with both generic (operational) and specific (very operational) strategies. However, in BVB, information/knowledge constraints such as cultural beliefs and extension service mistrust could be *"difficult to address"* with generic or specific strategies. An AEA in BVB bemoaned the difficulty in introducing new technology to some communities due to cultural beliefs.

"We have faced difficulties introducing improved maize seeds to some communities in the basin. There was pushback from some community members because they believed the improved varieties could not be used as sacrifice items to the gods during special occasions like festivals and funerals."

- *AEA, DOA-Lawra*

Furthermore, inputs and services costs are *"easy to solve"* constraints that require generic (operational) strategies to address. However, policy and resource-related are *"difficult to solve"* constraints that require both generic (structural) and specific (very structural) strategies to address.

These outcomes suggest that information/knowledge-related constraints could be easily addressed with specific or generic strategies with optimised internal or collaborative resources. In contrast, policy and resource-related constraints could be addressed with specific or generic strategies that seek to transform the agriculture system in both basins.

7.3.2.4 Strategies and timeframes to address critical constraints

Stakeholders in RVB and BVB proposed strategies/solutions within short, medium and long-term timelines to address the critical constraints., as shown in **Table 62** and **Table 63** below. This outcome helps determine what strategies institutions can internally or collaboratively develop to optimise or transform the agriculture system for SI.

Table 62: *Strategies and timelines for critical constraints in BVB. (Source: Fieldwork, 2021).*

	Critical constraint	Short-term (≤ 2years)	Medium-term (2 - 5 years)	Long-term (5 - 10 years)
1	*Unfavourable government policies on the input supply*	• A bottom-up approach to policy development		• Enforcement of guidelines around government policies • All stakeholders involved in agriculture policy development and implementation
2	*Poor soil fertility*	• Soil improvement in capacity building for community leaders and farmers • Participatory planning approach for soil fertility/improvement	• Prioritising compost making for soil-improving	• Resourcing institutions to support soil improvement at the community level (for example, funding for soil improvement research)
3	*Poor knowledge transfer due to the high rate of illiteracy*		• Design innovative communication tools or technologies that links local knowledge and Morden knowledge • Identifying community champions and building their capacity	• Developing farmer-based adult education programmes at the local level
4	*Limited access to agriculture inputs and services*	• Encouraging and providing incentives for the private sector to engage agriculture input supply and service delivery at the local level • Payment of credit with yields, especially input purchase	• Building and supporting functioning FBOs • Encourage the formation of FBOs to access credits/loans • Financial management training for farmers at the local level • Improving and supporting the VSLAs	• Providing opportunities to smallholder farmers for crop insurance during crop failure

Table 63: *Strategies and timelines for critical constraints in RVB. (Source: Fieldwork, 2021).*

	Critical constraint	Short-term (≤ 2 years)	Medium-term (2 - 5 years)	Long-term (5 - 10 years)
1	*Unfavourable government policies towards input supply*		• Broader consultation with all stakeholders at the local level on intended policies • Project pilots should involve all stakeholders for effective feedback before implementation	
2	*Inadequate agriculture resources (Eg. Finance & education)*	• Enhance capacity for community savings and loans groups	• Local-level resource management training Eg. financial management • Financial opportunities such as insurance, credit, and loans for agriculture activities	• Need for increased research on market systems in the area
3	*Poor/irregular community and farmer meetings*	• Encourage the formation and strengthening of FBOs • Enhancing the capacity of community leaders in environmental management	• Establishing guidelines to operationalise livelihood groups, including women groups and FBOs	
4	*Inadequate & High cost of agriculture inputs (Eg. Tractor services*		• Strengthening FBOs to access credit on inputs and loans for farming activities • operationalisation of the agriculture mechanisation centres	• Subsidies on farm inputs, fertilisers, pesticides, seeds, irrigation pumps
5	*Inadequate knowledge transfer among stakeholders & farmers*	• Increase radio discussions on environmental management and agriculture activities	• Increase the number and capacity of community-based assistants • Establishing agriculture information centres (for example Climate Advisory Resource Centres) at the community level	• Increase the number of AEAs and NGO support groups

The proposed short-term (≤ 2 years) strategies are the solutions institutions could implement internally with limited or no support from external collaborations. In contrast, medium-term (2-5years) strategies may require collaboration with external stakeholders. For instance, while farmers and input suppliers arrange credit payment with crop yields as an immediate strategy in RVB, the formation of functioning FBOs to access credit may take some time since it requires collaboration with financial institutions and government agencies to implement. Long-term (5 – 10 years) strategies are the type of solutions that mostly go beyond the capacity of local institutions. External institutions (private or public) at the national/international level are responsible for addressing long-term strategies. Long-term strategies are usually resources and policy-related measures around funding, insurance, infrastructure, research and subsidies. Most strategies in RVB and BVB are medium-term solutions requiring 2-5 years to implement using collaborative resources, knowledge, and action.

In summary, institutional stakeholders explored and categorised constraints that could hinder SI goals in BVB and RVB. Institutional constraints in both basins were similar under institutional subsystems and structural conditions but differed under governance dimensions and administrative levels. Critical constraints for both basins were identified through relationships by clustering and indicating networks among constraints. Institutional stakeholders in both basins agreed that the best way to address most constraints is through collaborations among institutions (within and outside the agriculture system).

However, institutional stakeholders in RVB believe more of their constraints are easy to address, while those in BVB consider more of their constraints difficult to address. Information/knowledge-related constraints are considered easy to address with generic and specific operational strategies, while policy and resources-related constraints require generic or specific structural strategies that could transform the agriculture system in RVB and BVB. These outcomes allowed institutional stakeholders to propose strategies with feasible timeframes (mostly medium-term) to address constraints in both basins.

7.4 Discussions: Institutional constraints and entry points for SI in Northern Ghana

This section discusses institutional constraints, entry points and potential solutions to achieve SI goals of productivity, resilience, efficiency, and equity in RVB and BVB. The findings are discussed alongside evidence from previous research conducted in Northern Ghana and other parts of semi-arid West Africa. The aim is to use the outcomes to re-emphasise existing evidence, close knowledge gaps and establish new ideas for SI in Northern Ghana. Recommendations for policy, practice, and research are also discussed to reduce constraints and enhance solutions to achieve SI goals in RVB and BVB.

7.4.1 Institutional barriers to agriculture innovation

7.4.1.1 Primary constraints to agriculture innovation

From the study, institutional stakeholders identified four critical constraints in RVB and five primary/critical constraints in BVB. The common critical constraints in both basins were related to policy, resources and knowledge/information, while unique constraints from RVB are natural resource-related, and those of BVB were related to community engagements and inputs costs.

The policy constraints in both basins are generally related to the delivery, distribution, and supply of inputs and logistics to operationalise agriculture programmes and projects like the PFJ. The study shows that unfavourable policies like fertiliser and certified seed price ceilings can exacerbate other constraints, making it the most relevant institutional constraint for implementing innovative strategies in both basins. According to Baanni (2020), certified seeds and chemical fertilisers are essential inputs needed for agriculture transformation and limited supply could affect other components of the agriculture system. A significant policy programme like PFJ was meant to transform the agriculture sector in Ghana by enhancing crop productivity for farmers through farm inputs and agronomic practices (Abdallah et al., 2021). However, inconsistent inputs supply and distribution to farmers, including AEA logistics, have hindered the potential of the PFJ programme since its inception in 2017. Reports indicate that the policy has failed to implement its framework of consistent input supply to farmers and the needed logistics for extension services (Baanni, 2020; PFAG, 2019).

The resource-related constraints include limitations in accessing education/training, inputs (fertilisers, improved seeds, pesticides), services (tractor services) and finance (credit, loans and funding). Stakeholders in both basins emphasised that bureaucracies within policy implementation and low capacity among local institutions to implement agriculture policy programmes worsen farmer resource limitations. However, some scholars have argued that local stakeholders need to harness the institutional partnerships necessary to access resources and capacities rather than rely on weak national policy implementation (Totin et al., 2018). The knowledge/information cluster includes constraints such as cultural belief systems and illiteracy among farmers that hinder institutions from disseminating new technology, innovation and information. Access to agriculture information/knowledge is central to building capacity and developing new skills within institutions to support farmers in adopting innovative strategies. The survey findings from chapters 5 and 6 show that farmers in RVB and BVB with access to expert advice/institutional support and those with access to information were more likely to adopt efficient on-farm strategies that increase crop yields. Lolig et al.'s (2014) work in Northern Ghana showed that households access to expert information from local government institutions enables them to build resilience against droughts and food shortages within their communities.

Furthermore, the finding shows that natural resource-related constraints, including soil infertility, erratic rainfall, and pest invasion, are more prevalent in RVB. As noted by stakeholders within RVB, inadequate research on biophysical properties, especially soils, may have worsened their biophysical risk perceptions on crop productivity, making it difficult for stakeholders to support farmers with their limited resources. Previous studies from the RVB indicated that degraded natural properties like soil infertility take more institutional resources than socioeconomic risk management, such as alternative livelihood options and financial management (Yomo et al., 2020). In BVB, the unique critical constraints were community engagements and inputs/services costs. Constraints leading to community engagement included inadequate education on environmental degradation, community bushfires, low knowledge transfer among institutions, unsustainable community/institutional projects, and absenteeism in community meetings. For instance, absenteeism from community meetings reduces institutions' ability to reach more farmers with the tools, strategies, and information needed to transform the agriculture system. This outcome may explain why only 36% of the farmers surveyed in BVB had access to information, compared to63% in RVB. The high inputs and services costs hinder stakeholders from supporting farmers in irrigation activities and sustaining agriculture projects within BVB.

7.4.1.2 Categories of constraints and their impact on agriculture innovation

The finding from the present study showed that most constraints in RVB and BVB were related to policy, effectiveness, institutional weakness and collaboration/interaction challenges. Policy-related constraints were many under institutional subsystems. Input suppliers, NGOs (BVB) and AEAs (RVB) indicated that policy-related challenges affected their work to support agriculture innovation. For instance, the policy around input supply that sets price ceilings for inputs and the bureaucratic processes involving supply affect input suppliers who transport inputs from the cities in the South to farmers in the North. This assessment is consistent with the evaluation of the PFJ programme by Baanni (2020), who discovered that the bureaucratic processes for certified seed distribution were a significant challenge for most input suppliers, especially those further away from the capital (Accra), where the PFJ secretariate is. Funding agriculture policy and programmes have been challenging for the public and private sectors at the local level, hindering the achievement of policy goals. According to Sidibé et al. (2018), policies intended to promote agriculture usually mismatch what they intended to achieve and what they accomplished due to funding lapses.

Moreover, the study has shown that most constraints under governance dimensions were related ineffectiveness of implementing policies and the instability with environmental and economic risks in both basins. An evaluation of the PFJ programme showed that even though the framework outlined the need for agriculture modernisation through digital systems and expansion of logistics, these objectives have been largely ineffective (PFAG, 2019). The PFJ programme largely concentrates on distributing inputs while neglecting other implementation actions within the policy framework. Instability within the agriculture system, including erratic rainfall, degraded soils, poor road network and inconsistent markets, hinder stakeholders from achieving their policy and programme objectives, especially for FBOs and AEAs. For instance, erratic rainfall resulting from climate change is expected to disrupt fragile agriculture systems like semi-arid areas, affecting household crop production and livelihood outcomes (Padgham et al., 2015; Zougmoré et al., 2014).

Another important finding from the study was that about 60% of all constraints under structural conditions were related to institutional weakness and poor interaction/collaboration among stakeholders in both basins. In a previous study on institutional collaboration in Northern Ghana, researchers found that partnerships and cooperation among local institutions had led to funding opportunities, resources and technology to support their work farmers (Yomo et al., 2020). The lack of collaboration/interaction in both basins may be due to internal institutional weaknesses, including inadequate funding, logistics and capacity to engage with other institutions, especially NGOs in both basins. This outcome re-emphasised past evidence suggesting that the capacity for local institutions is better established with diversified partnerships across the agriculture system that can enable agriculture innovation to occur (Totin et al., 2018; Yaro et al., 2015). Some studies acknowledged the usefulness of institutional collaboration, yet they found no evidence of direct benefit to farmers due to the disparity between national and local priorities (Ofoegbu & New, 2021; Osei-Amponsah et al., 2018).

Even though some categories of institutional constraints may be common, others differ across basins. In the RVB, constraints are particularly highlighted as research-related under institutional subsystems and local level under the administrative level categories. Research on natural resources in RVB is limited, especially for soils. The researcher's field observations in RVB revealed fewer biophysical research and field referrals (among research projects) compared to BVB. NGOs and community leaders in RVB perceived that most of their constraints were at the local level. NGOs, alongside community leaders, support agriculture and livelihood activities within local communities. However, poor collaboration among these institutions at the local level may worsen institutional constraints, such as agriculture information mistrust, resource conflict, and a low adoption rate among farmers. Multiple studies cautioned that institutional collaboration at the local level, especially for policy implementation, could be complex due to multiple actors from diverse backgrounds working with sometimes ambiguous regulatory structures and usually playing overlapping roles and with diverse interests (Nchanji & Bellwood-Howard, 2018; Ofoegbu & New, 2021).

Moreover, interesting findings from the BVB showed that institutional constraints were related to accountability, education/training, market systems and at the national level. The lack of accountability within national policies has facilitated the smuggling of inputs from Northern Ghana to the neighbouring countries causing shortages in input supply. The hoarding or smuggling of subsidised fertilisers and certified seeds is a critical challenge to the PFJ policy as it affects vulnerable social groups who may not be able to afford these inputs at higher prices from retailers (Baanni, 2020). A third of the constraints under the institutional subsystem were categorised under market systems. This outcome may be due to commercial groundnut farming in BVB. Mzyece (2021) found that even though legume sales in Northern Ghana were more than cereals, the quantity sold did not relate to profitability due to poor market access for some farmers.

7.4.2 Entry points for implementing SI

7.4.2.1 Who could address institutional constraints?

The study showed that solutions for institutional constraints are often both internal and external. Internal capacity and resources could enable institutions to address constraints independently, while some may require collaboration. The findings show that more than two-thirds of institutional constraints in both basins could be addressed through collaborative efforts, while less than one-third could be addressed independently. However, more constraints could be addressed collectively as local institutions in RVB, while more constraints could be addressed independently in BVB. A study in Northern Ghana showed that collaboration among institutions enabled financing, technical support, knowledge transfer, technology exchange, and resource to enhance institutional capacity, increasing resilience and productivity (Ofoegbu & New, 2021; Yaro et al., 2015). The DOA in both basins reported several collaborations and partnerships with local, national and international institutions to build internal capacity to handle constraints and support farmers to increase productivity and resilience. For instance, AEA's partnership with selected local input suppliers as part of the PFJ programme enabled quick input and timely inputs access, while partnerships with international organisations like the German agency for international cooperation (GIZ) enhanced capacity for farm demonstration in RVB and BVB (DOA-Bongo, 2020; DOA-Lawra, 2020). The findings show that FBOs were the only stakeholder group that required collaboration with other institutions to address their constraints. This outcome indicates how farmers are at the centre of the agriculture system and require partnership with all local agriculture institutions to adopt efficient strategies for resilience and productivity.

Even though there are few institutional collaborations at the local level, stakeholders in both basins considered these interactions/collaborations weak or inadequate. Upscaling agriculture innovation such as SI will require a strong partnership and collaboration among local stakeholders, especially between the public and private sectors, with diverse knowledge, resources and skills that support the agriculture system. For instance, natural resource management in Northern Ghana has been successful through collaborative efforts among local institutions in preserving forest resources from encroachment and degradation through using community by-laws (Boafo et al., 2016).

7.4.2.2 How to address easy or difficult constraints

Independent or collaborative solutions can also be easy or difficult, depending on the nature of the constraints. Constraints that are easier to address require system optimisation, while complex/difficult constraints may require system transformation. In RVB, the findings show that more than two-thirds of constraints could be addressed with optimised resources and capacities, while less than one-third may need system transformation. Except for NGOs, more than half of the constraints reported by FBOs, input suppliers, community leaders and AEAs are easier to address if existing resources are efficiently managed. On the contrary, over half of the institutional constraints (except for community leaders) could be difficult to address unless there is a system transformation at the institutional and community level. The possible reasons for differences in how constraints can be resolved in RVB and BVB could be related to how institutional stakeholders perceive their constraints under administrative and governance dimensions. In RVB, stakeholders categorised more constraints under the local level and ineffectiveness, while in BVB, stakeholders defined constraints under the national level and lacked accountability. Local-level constraints could be addressed when institutions prioritise efficiency in using available resources and capacities, while national-level constraints are often policy-related coupled with bureaucratic processes, which are challenging to deal with when accountability is absent. These outcomes are consistent with previous studies in Northern Ghana, suggesting that serious government bottlenecks, poor structures and low capacity make addressing constraints within the agriculture sector challenging (Diao & Hazell, 2019; Mawunyo & Woedem, 2013). However, local institutions can also mobilise internal capacity and resources to address urgent institutional and community constraints like deforestation and the impacts of climate change when government programmes fail (Boafo et al., 2016; Osei-Amponsah et al., 2018; Yaro et al., 2015).

For instance, critical constraints related to policy, resources and information are easier to address with resource optimisation in RVB, while more than two-thirds of policy and resource-related constraints may require system transformation in BVB. However, critical constraints related to natural resources in RVB, such as erratic rainfall or fall armyworm invasion, are external factors that severely impact agriculture, making it difficult to address. Many scholars affirm that biophysical risks like climate change pose a threat to the development of agriculture in West Africa, especially in semi-arid areas and will require firm policy and interventions that enable resilience to protect vulnerable livelihoods (Padgham et al., 2015; Partey et al., 2018; Zougmoré et al., 2014). On the other hand, constraints related to cost, especially for inputs and services in BVB, could be addressed when institutions collaborate to provide alternative options like cost-sharing, composting, and seed-growers to access these inputs. According to Rosenstock et al. (2018), cost-sharing for resources is the best option for smallholder farmers to access inputs and services than government subsidies which are inconsistent. Constraints related to community engagement in BVB are easier to address with incentives but, at the same time, complex to address due to language barriers or cultural beliefs that hinder information dissemination at the community level.

Furthermore, the present study showed that national and local institutional collaboration could address the most difficult/challenging constraints. For instance, subsidised PFJ input delivery delays could be addressed with negotiations between private input manufacturers and public procurement at the national level, including the local input suppliers and DOA. Collaboration through interaction can reduce bureaucracies by shortening the value chain of input delivery from national manufacturers to local suppliers and farmers (Hazel et al., 2019). Optimising resources and capacities could address institutional constraints through collaborations at the local level, especially in RVB. There were no constraints in RVB that were internally difficult to address, while in BVB, a few constraints, including poor soils, low adoption rate and conflicts over resources, could be internally difficult to address unless there is a system transformation. Only about one-fifth of the internal constraints in both basins are internally easier to address with system optimisation.

7.4.2.3 Generic and specific interventions for SI

From the study, stakeholders in BVB, especially FBOs and input suppliers, perceived that their constraints might require generic interventions, while those in RVB, especially AEAs, consider that their constraints might need specific interventions to address. The possible reason for the outcome in BVB could be due to national-level incompetencies and bureaucracies cutting across all sectors, not just agriculture. According to Diao & Hazell (2019), the private sector's role in agriculture policies and programmes in Ghana has been hindered by bottlenecks and ineffectiveness at the national level. Public sector reform could help address general constraints across all sectors, including agriculture. In RVB, a specific local-level policy strategy targeting AEAs could help address logistical and personnel challenges to enable efficient extension services for resilience and productivity.

Also, the study found that FBOs in both basins believe most of their constraints would need generic interventions that could address all constraints across institutions. This outcome is because farmers rely on the proper functioning of all institutions within the agriculture system to be efficient, resilient and productive. This finding is consistent with a previous study that showed coordination among stakeholders in some areas of Northern Ghana enabled institutions within the cereal value chain to address some of their challenges leading to a positive outcome for farmers (Kolavalli, 2019). However, Ofoegbu & New (2021) found that even though there is coordination between some stakeholders in Northern Ghana, farmers do not benefit due to the disconnect between local needs and national priorities. At the operational level, stakeholders in both basins believe that addressing institutional constraints will require both generic and specific interventions. This outcome indicates the need for institutions to use interventions that target specific constraints and those that could address different types of constraints within the agriculture system. Effective monitoring and evaluation through the policy or programme implementation could be useful in diagnosing constraints and understanding the interventions to apply (Mawunyo & Woedem, 2013; World Bank, 2017).

Another critical finding from the present study showed that stakeholders in BVB believe some structural and operation constraints could be easier to address. For instance, structural constraints, including unsustainable projects and insufficient tractor services, and operational constraints, including low education on environmental challenges, language/communication barriers and poor knowledge transfer, could be addressed easily with optimised institutional capacities and resources. Previous studies show similar results indicating that well-organised local institutions can attract external support to sustain their activities (Bonye et al., 2012; Yaro et al., 2015). Some structural and operational constraints in BVB may be more difficult, requiring institutional transformation. These difficult constraints include a lack of project funds (very structural), inadequate logistics (structural), cultural beliefs (very operational) and mistrust of extension services (operational). Several studies have indicated that the overreliance on external donors to fund agriculture policies and programmes in Ghana makes their sustainability unlikely, making other constraints like inadequate logistics and poor extension services difficult to address (Benin, 2019; Hazel et al., 2019).

In RVB, stakeholders considered constraints such as unfavourable input supply policies (very structural), inadequate fertilisers/certified seeds access (structural), late input delivery (very operational) and low soil fertility (operational) as constraints that may be easier to address with optimised institutional resources and capacities. However, an institutional transformation could be the option for some structural and operational constraints, including climate change/erratic rainfall (very structural), inadequate field logistics (structural) and pest and disease infestation(operational). Constraints like climate change will be difficult to address at the local level without a national and international policy or action front that targets different institutions at all levels (Partey et al., 2018; Yaro et al., 2015).

7.4.2.4 Interventions and timelines for SI

Stakeholders proposed possible interventions and timelines to mitigate the critical constraints to achieve SI goals in both basins. Stakeholders proposed that constraints could be addressed with short, medium and long-term implementation action plans. These proposed action plans could enable institutions to optimise or transform their platforms and the agriculture system. The present study shows that proposed short-term interventions in both basins are operational and can be resolved independently within institutions by optimising available resources. In BVB, enhancing the capacity of stakeholders and smallholder farmers can strengthen VSLAs, FBOs, local leaders and the entire community to enable access to resources (finances and inputs) and increase knowledge on environmental management. For instance, addressing knowledge transfer gaps among stakeholders and farmers in the short term may involve increased radio discussions and outreach at the community level. In RVB, the short-term action plans focus on the approaches to engaging communities and stakeholders for policy development, research engagement and input access. These suggested approaches are participatory and collaborative actions to achieve Policy, research and implantation outcomes that benefit all relevant stakeholders and social groups. For instance, addressing poor soil fertility in RVB requires capacity building and participatory soil management planning with community leaders and farmers.

In addition, the present study indicates that the medium-term action plans to enable SI in both basins could be collaborative efforts between local institutions. Stakeholders may collaborate and use specific and generic strategies to optimise or transform institution and agriculture systems between two to five years. From the study, most proposed strategies/interventions could be addressed within the medium term with appropriate stakeholder collaborations and resources. In BVB, the medium-term action plans are about broader community engagement for policy development or project piloting, education/training on financial access or management, strengthening social support groups for resource mobilisation and providing localised knowledge-sharing platforms accessible to all social groups. Similarly, in RVB, stakeholders proposed that interventions for critical constraints in the medium term could provide practical skills for compost making and accessing research information, identifying and building the capacity of community champions and social groups and enhancing community knowledge on financial literacy. Financial management, strengthening social groups, and information dissemination were the common strategies to address constraints in the medium term to achieve equity, efficiency, resilience and productivity as SI goals in RVB and BVB.

Moreover, the findings show that the proposed long-term action plans are very structural and very operational interventions that may require specific policy or programme pathways to transform the agriculture system. Due to the nature of long-term action plans, collaborative efforts from all stakeholders and social groups are required to ensure their sustainability for an extended period. The proposed long-term action plans involve heavy resource commitment and are often carried out as a national project to transform agriculture. In BVB, stakeholders proposed that critical constraints could be resolved through increased agriculture research on market systems, subsidies for inputs and technology and an increasing number of AEAs to meet the FAO standard of 1:500 (AEA to farmer). In RVB, stakeholders concluded that the most critical constraints could be addressed with interventions such as enforcing policy implementation guidelines/framework, resourcing institutions for biophysical research, developing adult education programmes and providing opportunities for crop insurance against climate change-related crop failure. Long-term action could be bureaucratic during implementation due to multiple stakeholders or institutions involved; participatory processes involving all stakeholders need to be in place to reduce the bottlenecks for a policy or programme implementation.

7.5 Practical Recommendations for SI

7.5.1 Policy

Existing policy programmes like the PFJ could be enhanced to include other SI goals, including resilience, efficiency and equity, rather than just focusing on productivity. Achieving these SI goals means the PFJ programme must focus on reducing government bureaucracies in policy implementation on inputs delivery to farmers and logistics supply to institutions, especially AEAs. The SI framework could be helpful for the PFJ input delivery, where the agriculture system supports equitable resource allocation among social groups, especially vulnerable groups. The PFJ programme needs to simplify and decentralise the certification process to allow input retailers and producers from Northern Ghana to have a flexible and less complicated registration process. PFJ could achieve SI goals when the government hires more AEAs to reduce the high farmer-to-AEA ratio, enabling more efficient farmer outreach strategies that enhance resilience and productivity. Infrastructural (such as irrigation facilities, road networks and storage facilities) and human investments (education and training) can help reduce the impact of climate change and provide biophysical stability within the agriculture system. These investments will require firm policy, steady funding and technical support from the national level to local institutions, which are mandated to collaborate and address critical constraints.

7.5.2 Practice

Private sector investments in crop production can enable the easy flow of resources into the agriculture system for institutions to support farmers. For instance, private sector investment in the cocoa sector of Côte d'Ivoire significantly improved local institutional support, which then led to the enhancement of livelihoods of smallholder farmers through increased employment opportunities, market access, high productivity, and better product quality and technological know-how (Kanga et al., 2018). Innovative ways to improve access to timely and valuable information among institutions and farmers, especially research information, could achieve SI goals in both basins. Achieving an effective, stable, and accountable governance system will require strong collaboration among local and national institutions. For instance, stopping inputs smuggling into Burkina Faso will require collaborations with the security forces, community leaders and the judicial system to penalise and convict perpetrators, serving as a deterrent and strengthening accountability. Education and capacity training, especially for institutions in BVB, could offset some constraints at the community level, including inadequate logistics and human capacity. These actions must be followed with consistent and frequent interaction, collaboration and partnership among institutions with diverse capacities, enabling local institutions to secure assets and infrastructure to achieve SI goals.

Achieving SI goals in RVB will require institutions to apply more specific interventions at the local level to reduce AEA constraints while addressing FBO constraints with generic interventions.

7.5.3 Research

Increased investments in research on biophysical properties, especially soils in RVB, could help address institutional constraints related to natural resources. Further research could be conducted within the following areas: *i)* Government bureaucracies and their impact on agriculture policy and programmes at the local level, *ii)* Sustainability of agriculture projects and programmes to achieve system transformation, and *iii)* Community engagement strategies and their influence on agriculture development.

7.6 Summary

This chapter investigated and compared institutional constraints and entry points for implementing SI in RVB and BVB. From the findings, 25 constraints were identified in each basin and clustered into critical constraints in both basins. Three constraints related to policy, resources and information/knowledge transfer were identified as similar between both basins. However, constraints related to community engagement and input cost were unique to BVB, while those related to natural resources were unique to RVB.

Also, more constraints in BVB were found at the national level and could be due to challenges within agriculture policy, education/training, ineffectiveness, accountability, institutional weakness and poor collaboration/interaction. However, in RVB, institutional stakeholders believe more of their constraints were at the local/community level, resulting from challenges within agriculture policy, research, ineffectiveness, institutional weakness and poor collaboration/interaction. Overall, constraints faced by institutions in both basins were related to agriculture policy, governance ineffectiveness and institutional weakness.

The study found that most constraints in RVB were easier to address if available resources were optimised through institutional collaboration using specific interventions. However, most constraints in BVB might be difficult to address unless there are collaborative efforts among institutions to transform the agriculture system with mostly generic interventions. The findings further show that short-term interventions to address constraints could be done independently within institutions, while medium and long-term interventions require collaborative efforts with all stakeholders within the agricultural system. However, medium-term interventions involving financial management, strengthening social groups and information dissemination are needed to address the most critical constraints in both basins.

CHAPTER 8
CONCLUSION

8.1 Introduction

The chapter describes how the study's key findings on water/soil-related risks and strategies, access to agriculture resources, demographic characteristics, institutional collaboration, and household production needs address the research aim and contribute to evidence for building agricultural sustainability and SI in semi-arid Northern Ghana. The study's limitations, general implications for future research, policy and practice, and the plans for potential research dissemination are also described in this section.

8.2 Key research findings and their implication for SI

This PhD thesis aimed to determine the factors contributing to crop productivity differences between RVB and BVB and how these factors could influence the implementation of SI within smallholder agriculture systems in semi-arid Northern Ghana. The aim of this study was achieved by developing an SI framework to assess and compare the biophysical, socioeconomic and institutional characteristics of crop farming, to derive lessons for implementing SI in semi-arid Northern Ghana. Considering the research aim, this study has provided evidence that Sustainable Intensification can be more effectively realized within smallholder crop production systems in the semi-arid regions of the Red Volta and Black Volta Basins in Northern Ghana, provided there is a strategic emphasis on the following pivotal factors: *i)* Managing water and soil-related risks, *ii)* accessing to agriculture resources, *iii)* considering household demographic dynamics, *iv)* enhancing institutional collaboration/interaction and *v)* addressing household food and market needs.

8.2.1 Water and soil-related risks as determinants of productivity differences

Farmers' perceptions and on-farm management strategies related to water and soil properties are the important biophysical factors that shape crop productivity and yield differences across Semi-arid Northern Ghana. In the case study areas, the study found that farmers in RVB with lower yields perceived temperature increases and soil nutrient deficiencies as high-risk factors that negatively impact crop production. Meanwhile, in BVB, farmers who perceived dry spells as a high-risk factor also recorded lower yields than those who perceived it as a low-risk factor. These findings suggest that farmers' experiences and their ability to cope with climatic/water and soil-related risks affect their productivity levels. Similarly, farmers who perceive biophysical risks as high-risk factors to crop production tend to adopt more strategies to respond to these risks, especially in RVB. These findings align with past evidence in Northern Ghana, indicating that farmers adopt several strategies to cope with rapidly changing environmental risks like climate change (Boansi et al., 2017; Dakyaga et al., 2020).

Importantly, farmers who intensified on-farm strategies to cope with biophysical risks could not meet their expected yields unless their actions were implemented alongside support mechanisms such as expert advice and/or extension services, information delivery (climate services), education and FBOs support. These support services are often linked and enable farmers to adopt efficient and resilient strategies that enhance crop productivity and income. Pretty et al. (2011) identified similar findings when assessing several SI projects in SSA and found that access to agricultural support services enabled farmers to adopt efficient strategies and increase yields. This result adds to the evidence that adopting more on-farm strategies to cope with perceived risks without adequate capacity to implement them effectively could lead to maladaptation. SI in semi-arid Northern Ghana will require adequate capacity building and training at the farm level to enable farmers to manage increasing climatic and soil-related risks.

In addition, water availability for irrigation will be crucial in managing high-risk factors such as dry spells and high temperatures that have been found to affect productivity. The study has shown that farmers in communities closer to permanent water sources with access to dry season irrigation farming tend to increase yield levels and incomes more than those further away from water sources without any irrigation options. Climate change is expected to increase the incidence of water-related risks, such as dry spells in semi-arid areas of West Africa, making agricultural water supply a key issue for agrarian communities presently dependent on rain-fed farming. Without an alternative water supply systems for irrigation in communities without permanent water sources, achieving SI goals of productivity and resilience in the case study areas will be impossible. National and local stakeholders must prioritise resources and investments into small dams, water retention strategies and irrigation technologies for farming communities across Northern Ghana to achieve an SI system that can sustain both subsistence and commercial farming. Although these strategies may be expensive for farmers, some authors argue that cost-effective alternative techniques, like Zai pits and half-moons, could be practised in smallholder systems as part of the SI strategy (Zougmoré et al., 2014).

8.2.2 Access to agricultural resources as determinants of crop productivity differences

Access to agriculture resources, including capital investments, input availability (fertlisers and improved seeds) and timely services, promotes crop productivity and influences yield differences. Farmers in both basins who were found to have access to financial capital through loans, savings, and credit tended to have higher yield and income levels, increase farm investments and adopt more efficient on-farm strategies. This finding is consistent with the existing research suggesting that access to capital or wealth enhances farmers' investments in new technology, inputs and strategies that increase yields (Amegnaglo, 2018; Wood et al., 2014). However, farmers in RVB were more likely to have diverse sources of capital, including credit facilities, savings and alternative livelihood incomes, than farmers in BVB. This finding presents an opportunity to diversify the livelihood activities in the BVB that could generate off-farm incomes to support farming. While SI will require heavy investments at the national level, farmers can also leverage available financial schemes like the VSLAs to raise capital for farming. The available capital from VSLA schemes, often in the form of soft loans, could enable farmers to access some key inputs such as fertilisers and improve seeds which were found to increase yields and income levels for farmers significantly.

However, farmers in RVB who access more agriculture inputs and support services were found to have reduced yields, while those in BVB had increased yields. The finding could be due to farmers in RVB's overdependency on the inconsistent government-subsidised resources, often constrained by frequent delays due to weak policy programmes. Farmers who could access fewer (but timely) resources from private sources such as input retailers or FBOs significantly increased their yields and profits, especially those in BVB. For instance, farmers participating in FBO activities could increase their farm investments, access inputs, practice efficient strategies and eventually improve yields and incomes, although fewer farmers join FBOs in both basins.

Unfortunately, the study found that public institutions mandated to provide subsidised inputs and support services lack solid agriculture policy backing, inadequate capacity (logistics and staff training), and poor knowledge transfer to implement SI effectively in Northern Ghana. Several studies have reemphasised how institutional weaknesses around agriculture policies, funding and human capacity have drawn back SI efforts in most developing countries (Schut, Klerkx, Rodenburg, Kayeke, Hinnou, et al., 2015; Schut, Rodenburg, Klerkx, Kayeke, van Ast, et al., 2015).

The evidence from the study implies that agriculture resources accompanied by are critical elements for enhancing yields, efficiency, resilience and equity within the agriculture system; as such, a key dimension of actions to support SI in future will be to address the institutional weaknesses that limit effective policies, adequate logistics and information transfer in both basins. Also, SI actions must create or enhance opportunities outside farm work for farmers to increase their income, enabling them to increase farm investment for higher productivity, especially in BVB. Alternatively, or in combination, VSLAs and credit opportunities through small grants or loan facilities from the government or private sector could help raise capital for the most vulnerable farmers to invest in crop production. Public-private partnerships will be a good SI strategy that allows the private sector to step in with reasonable, cost-effective and cost-sharing options for inputs and services when government programmes are delayed, especially in RVB.

8.2.3 The role of household demographic characteristics in crop production

Household demographics, such as the age and gender of household members, as well as their educational level, play a crucial role in shaping farmers' perception of risks, their on-farm practices and strategies, their ability to access and utilise resources, their participation in off-farm activities, their crop yields, and their overall income levels. This finding is in line with several studies in West Africa that have found household demographic characteristics to be crucial determinants of perceptions, practice and productivity (Deressa et al., 2011; Lawson et al., 2020; Nyantakyi-Frimpong, 2017).

Women, less educated farmers, and older individuals residing in communities lacking permanent irrigation water sources have been identified as particularly vulnerable social groups. The vulnerability of these social groups was due to their lower off-farm income sources and poor access to resources that would enable them to adopt effective and resilient strategies for boosting productivity. In Northern Ghana, cultural norms often perpetuate gender inequalities, exacerbating the vulnerabilities of women farmers residing in communities such as Yagture in BVB, which lack both on-farm and off-farm work opportunities. For instance, women in all the communities in the case study areas were not permitted to own cropland, although they could access some for farming through their family or community, or by leasing land. Lack of land tenure security often disincentivises farmers from investing in strategies that could enhance biophysical properties like soils. Older farmers may lack physical strength, while less well-educated farmers may lack key information to access resources or implement certain strategies. Robinson et al. (2015) noted that compound vulnerabilities at the household level could weaken farmers' ability to participate in activities or adopt efficient strategies to achieve SI goals.

The results have shown that men, educated farmers, and young individuals in communities with access to water sources for irrigation exhibit higher levels of resilience and lower vulnerability. These findings can be attributed to their perception of biophysical risks as less threatening to farming activities and their ability to implement efficient and adaptive strategies that enhance productivity. Higher education levels also provide farmers with alternative sources of income generation and the ability to invest more in farming, thereby increasing their adaptive capacity and improving productivity. Deressa et al. (2011) discovered that education gives farmers more social leverage to reduce biophysical risks, increase resilience and enhance productivity.

The intersectionality of gender, age and education implies that less-educated older women, especially in communities without water sources, are the social group who may struggle most to implement SI actions. The most vulnerable social groups with poor yields and limited off-farm opportunities, especially in BVB, may overexploit ecosystem services, resulting in further biophysical degradation, which could challenge SI efforts. However, well-educated young men in communities with water sources for irrigation are the less vulnerable and potentially the most resilient group with the social and economic capital (from formal employment opportunities) to succeed in the SI farming system in Northern Ghana. The most resilient social groups, characterised by their ability to utilise available resources effectively and wield social influence, have the potential to intensify crop production and achieve higher yields. However, this heightened intensification of production could lead to the overexploitation of biophysical and socioeconomic systems, which may prove unsustainable in the long term. SI practice may require constant negotiations between social structures, especially between the vulnerable and resilient groups, while recognising vulnerabilities and power dynamics within the agriculture system (Robinson et al., 2015; Theriault et al., 2017). A key role of institutions such as the DOA, NGOs and traditional authorities should be to mediate these negotiations to establish equitable resource distribution across all social groups (Struik & Kuyper, 2017).

8.3.4 Institutional collaboration/interaction and its influence crop productivity

The capacity of institutions at the local level to address critical constraints, such as poorly implemented agriculture policies, inadequate extension capacity (logistics and training), and poor knowledge transfer, strongly affect the quality, scale and impact of support services that enhance agriculture innovation to boost productivity. The findings from the study showed that institutions in BVB considered these critical constraints difficult to address because of poor collaboration and interaction among relevant stakeholders. On the contrary, institutions in the RVB considered these critical constraints relatively easy to address due to their fostered collaboration and interaction among stakeholders. Several studies have indicated the significance of institutional collaboration in raising adequate funding and providing technical support for SI activities across SSA (Schut, Cadilhon, et al., 2016; Totin et al., 2018). The study further revealed that institutional collaboration/interactions might be the most viable pathway to addressing the most difficult constraints that could not be addressed within institutions, especially in BVB. However, Ofoegbu and New (2021) found that institutional collaboration does not always benefit farmers due to the disconnect between local and national priorities, especially climate services.

Moreover, the study showed that while short-term solutions to addressing institutional constraints may be possible with internal resources and capacity, medium and long-term solutions relating to financing, strengthening social groups, and technology dissemination will require collaboration and often structural changes in government policies and institutions. SI should be considered a strategic policy and practice opportunity to transform the institutions, support the most vulnerable groups and seek to bridge the gaps between local needs and national priorities. Dakyaga et al. (2020), in their policy recommendations for SI in Northern Ghana, suggested that government must provide incentives for local stakeholders to fully partake in policy negotiations around trade-offs between long-term sustainability goals and short-term production needs.

These results imply that developing a productive, resilient, efficient, and equitable agricultural system in semi-arid Northern Ghana requires strategic efforts to strengthen collaborative channels and linkages between diverse institutions and stakeholders. By harnessing their collective resources and capacities, institutional collaboration in both basins can address resource challenges and provide advisory and extension services to drive the adoption of sustainable on-farm practices that boost resilience and productivity.

8.2.5 Household food and market needs as determinants of crop productivity

Farmers' choice of crops, farm investments, cropland size, inputs, and on-farm strategies are significantly influenced by their preferences to produce for household food consumption or market demand. This decision has a direct impact on the efforts made by farmers to enhance their yield and overall agricultural productivity. The findings indicate that farmers in RVB allocate a higher proportion of their resources, such as arable land, financial capital, and inputs, towards cultivating cereal crops for household food needs, particularly maize and millet. The more subsistence cropping system in RVB results from the need to cater to the larger household size compared to BVB, thus requiring increased production of food crops to meet domestic consumption requirements. However, farmers in BVB tend to produce more secondary crops (primarily groundnuts) for the market, even though they also produce adequate cereals like maize for household use.

These results imply that the needs of households drive the pattern of their cropping system, highlighting the importance of taking into account household agriculture needs when designing SI interventions. For instance, food security needs will be a priority in RVB, while market needs will be prioritised in BVB when implementing an SI. However, farmers in both basins could benefit from SI interventions that support increasing yields to meet household needs and market demand. An integrated approach is necessary when designing SI approaches so that farmers' productivity needs are central while sustainability goals of efficiency, resilience and equity are framed around those needs. Several studies have noted that a win-win approach is needed in balancing environmental goals with productivity and socioeconomic needs when designing approaches for sustainable farming systems in developing countries (Brouwer et al., 2020; Dekeyser et al., 2020; WEF, 2017).

8.3 Significance of the study

The present study makes several contributions to knowledge on crop productivity, food systems and entry points for SI in semi-arid Ghana and West Africa. Firstly, the evidence from the study showing that each basin defined its own productivity goals based on its needs can contribute to the existing SI concept by Garnett et al. (2012), indicating that agrarian communities define their productivity outputs in SI practice to meet their food security and livelihood demands. This concept allows producers within the agriculture system to produce the type and quantity of food they "need" rather than what they "want", leading to reduced over-exploitation of environmental and socioeconomic capital (Garnett et al., 2012). For instance, the study found that the larger household size and population density in RVB compels smallholder farmers to make subsistence farming a goal by intensifying on-farm adoptions to produce more food crops to feed the growing household/population size. In contrast, farmers in BVB can afford to balance subsistence and commercial farming by growing both food crops and cash crops due to their low population density and household size. However, the results show that farmers in RVB's attempt to intensify productivity to meet household food demand could have led to a more negative perception of biophysical risks. This outcome adds to the growing food systems literature indicating that high population density increases food demand, and an attempt to produce more to meet that demand could exacerbate biophysical risks (Cassman & Grassini, 2020; Godfray et al., 2010; Pretty et al., 2011).

Secondly, the findings from the study provide a suitable setup for the SI framework that suggests SI-in-practice is not a set of specific strategies but guiding principles that could be applied within existing agriculture production systems, drawing from various approaches such as CSA, agroforestry, conservation agriculture and precision agriculture (Campbell et al., 2014; Garnett et al., 2012; Pretty et al., 2011). The present study has shown that the current agriculture strategy in Northern Ghana, like the PFJ programme, possesses some biophysical, socioeconomic and institutional characteristics that could be recalibrated to achieve outputs beyond the current goal of productivity and include efficiency, resilience and equity as agriculture system targets. For instance, the study has shown that smallholder farmers in both basins with access to adequate agriculture services, such as advisories, extensions, and information, could efficiently adopt strategies to enhance productivity, resilience, and equity. This evidence further contributes to the sustainable agriculture literature that suggests that achieving a sustainable food production system in semi-arid areas requires adequate extension and information services benefitting all social groups (Antwi-Agyei et al., 2021; Setsoafia et al., 2022).

Thirdly, the current study provides further insights into a growing body of literature that challenges the notion that increasing agriculture inputs will increase productivity outputs. The present study shows that farmers in RVB with access to more inputs to increase adoption of on-farm strategies had a reduced productivity effect with lower yields unless inputs and adoption are done with access to expert advice, which significantly increases yields. This finding contributes to a section of productivity literature in Northern Ghana suggesting that increasing subsidised inputs, especially from government programmes to smallholder farmers without proper targeting or adequate capacity training to use input, could result in an adverse effect or maladaptation (Lolig et al., 2014; World Bank, 2017). However, existing literature suggesting increased agriculture inputs increase outputs in Northern Ghana (van Loon et al., 2019; Zougmoré et al., 2016) may be challenged as the findings show support services like education, advisory and extension must accompany inputs to achieve increases in output. These findings provide critical lessons for the PFJ programme, where the government's goal of using input intensification to achieve crop production needs to be accompanied by adequate advisory services to enhance adoption efficiency.

Fourthly, the present study adds to the current understanding of trade-offs that can occur within SI. Current literature indicates that trade-offs within SI practice are inevitable due to the multiple dimensions and goals an agriculture system could achieve, where increasing one output may harm other outputs (Dekeyser et al., 2020; Robinson et al., 2015). The present study has shown that farmers in RVB and BVB must make difficult choices between and within biophysical and socioeconomic objectives to meet their food security and livelihood needs. The study has shown that farmers must contend with complex and often opposing choices to achieve desirable SI goals within each basin. These complex choices include; either growing cash or food crops; using subsidised/certified inputs or unsubsidised/conventional inputs due to PFJ inputs delays; relying on remittances or alternative livelihood incomes due to low crop yields, and practicing dry-season farming or engaging in off-farm activities due to lack of water sources for irrigation. For instance, the present study discovered that smallholders in RVB without water sources for dry season irrigation farming often engage in multiple off-farm activities, including migration, to generate incomes to supplement crop yields from rain-fed farming. However, migration may reduce the active labour force for farm work overtime when seasonal migrants find alternative livelihood options better than farming in the cities. Further findings from the present study showed that the ultimate goal of farmers in both basins was to intensify relevant crops through subsistence or commercial farming, not sustainability. These findings re-emphasise previous knowledge in SI literature, indicating that smallholder farmers in Northern Ghana are often concerned with short-term productivity or economic gains over long-term environmental sustainability gains by intensifying input use and increasing biophysical risks (Dekeyser et al., 2020).

Lastly, this study makes methodological contributions to how the SI framework could assess existing smallholder agriculture systems in developing countries, especially West Africa. The commonly used frameworks for examining SI are often based on triple-bottom-line assessments (Crewett, Sieber, et al., 2006; Fallah-Alipour et al., 2018b; Gaviglio et al., 2016; Peano et al., 2015) using biophysical, social and economic domains, or a single-dimensional assessment using only one of the three domains (N. E. Sabiha et al., 2016; Schut, van Asten, et al., 2016). Based on the literature review and preliminary knowledge of the case study areas, the present study modified existing frameworks used in several SI studies by including the institutional dimension as an SI domain. Formal and informal institutions are critical to rural agriculture by supporting smallholder farmers with inputs and services needed for crop productivity (Schindler et al., 2015; Yaro et al., 2015). Including the institutional component was a strength in the conceptual framing, as assessing the role of supporting institutions and their constraints meant that the study looked beyond the farm and household levels to the larger food system, bringing insights from diverse perspectives. This study could be the first SI assessment comparing two transboundary basins within different administrative regions in Northern Ghana and with similar ecological zones (semi-arid). The SI framework in this study could be applied to assessing different case studies in developing countries, especially in smallholder farming systems in dry areas of Africa.

8.4 Limitations of the study

Even though the present study has contributed to food systems and SI knowledge in Northern Ghana, it also has a number of limitations, including a limited scope, short timelines, a narrow agriculture perspective and a selective methodology.

The geographical scope of the case study for comparison covers only two semi-arid areas in RVB and BVB of Northern Ghana. Other semi-arid areas in Ghana, especially along the coastal belt in the Greater Accra region, were not considered for the present study. For this limitation, designing national agriculture policies based on findings from semi-arid Northern Ghana may be too generalised due to different locations' social and cultural dynamics. Specific recommendations for sustainable agriculture policy and practice in this study may not apply to other ecological zones in Ghana and West Africa, even though the methodology could be helpful to achieve similar findings in other locations. Also, the study insufficiently explored the socio-anthropological perspective, particularly the impact of cultural norms, historical legacies, and colonial histories on the vulnerability and adaptive capacity of the communities. This was due to the multiple dimensions the study looked at which limited the scope of the research.

The limited timeframe for the present study did not allow for a longitudinal study, which could have enriched the data collected and enhanced the findings discovered during the analysis. For instance, a more extended timeframe could have enabled the collection of household biophysical and socioeconomic time-series data enhancing the comparative study within and between the case study sites. The shorter timeframe for the present study could not allow for collecting and analysing soil sample data across the case study sites, therefore relying on secondary data sources for such information. The methodology for biophysical (water, soil, ecosystem and crop) analysis was perception-based instead of lab-test analysis, which could have produced more accurate results. Even though perception data was valuable and helped achieve the study's objectives, farm-level water and soil testing could have provided a more specific, quantitative biophysical information than the perception data at the household, community, and basin levels used in the present study.

Again, the multidimensional nature of the SI framework used in the present study required mixed qualitative and quantitative data collection and analysis methods, which posed some challenges. For instance, while objectives one and two heavily leaned on quantitative data and analysis, objective three mainly relied on qualitative data analysis, which became a challenge to synthesise the study's outcomes. The lack of focus on one methodology may have reduced the rigorous data analysis that could have been conducted for either purely quantitative or qualitative analysis. Regardless of these limitations of mixed methodology, it enabled the collection of complementary data useful for context analysis of the case study.

Lastly, the present study had to be limited to meet the institutionally determined word count requirement for submitting a standard PhD thesis. The study only focused on crop production for SI, leaving out animal production and aquaculture as a choice. Even though crop production is the leading agriculture activity in semi-arid Northern Ghana, the finding would have been interesting to see how crop productivity and animal production interact for SI. The study's mixed methods and comparative nature enabled the researcher to collect large amounts of data animal and aquaculture that ultimately had to be excluded from the analysis. The data that could not be used in the present study would be analysed and used for future research articles. Also, the study's reliance on an indicator-based approach, while beneficial for simplification, may overlook nuanced intricacies inherent in multifaceted agricultural systems. An alternative approach would have been the use of a composite regression model that looked at all variables, or combinations of variables, to assess their relative importance. The study tried to reduce its limitations, including scope and methodology, by relying on secondary data and previous research in semi-arid Ghana.

8.5 General Recommendations

8.5.1 Future Research

The present study recommends that future studies expand the scope of the SI study to include longitudinal data collection, other agriculture sectors, and different ecological zones in Ghana and greater West Africa. The present study's household surveys were conducted over a year from 2020 to 2021, which was insufficient for a longitudinal study. Conducting a longitudinal study of five years or more could enable researchers to track changing internal and external factors influencing the agriculture system, helping to understand the long-term patterns and trajectories for biophysical, socioeconomic and institutional properties in semi-arid Ghana. Research areas needed for longitudinal studies may include changing household and farm-level productivity, income, on-farm and off-farm activities, soils, water and ecosystems change in both RVB and BVB.

Again, future research can build upon the findings from the present study to expand the scope of the agriculture sector used for the study. As noted earlier in the study's limitations, crop production was only used because of its dominance in the case study area and the attempt to reduce the scope of the study to meet the thesis word count requirement. Future studies could combine crop and livestock production to understand how their relationship enhances SI goals within RVB and BVB. The SI methodological framework for the present study could be used for comparative studies or individual case studies in different ecological areas across Ghana and West Africa. For instance, SI studies could compare biophysical, socioeconomic and institutional characteristics of the semi-arid ecological zones in the coastal and savanna zones of Ghana/West Africa. These types of studies should consider integrating both yield and price expectations to provide a more comprehensive understanding of farmers' decision-making processes in crop production. Also, future research should delve deeper into the influence of culture, history, and colonial legacies on regional intensification practices, emphasizing the historical context of resource access and control.

Lastly, the SI framework could help assess existing agriculture implementation strategies like CSA, agroforestry and conservation agriculture to understand how they could achieve the SI goals. More specifically, the framework could be used as a monitoring and evaluation tool for assessing the government PFJ programme implemented in the case study areas and across Ghana for the past few years.

8.5.2 Policy contributions

The present study could contribute to achieving SI goals in Northern Ghana through policy initiatives on productivity, agriculture resources and gender equality or equity. National agriculture policies like the PFJ to boost agriculture must not be generic but more targeted depending on an agriculture system's needs. Currently, the PFJ policy is keen on promoting specific crops, especially maize, across the country, regardless of geographical location. However, the crop production systems across Northern Ghana have diverse productivity interests, which such policies need to identify and boost while introducing new ones. Even though the government programmes are meant to achieve short-term productivity goals, current agriculture policies need other strategic goals, including achieving efficiency, resilience and equity that could sustain the productivity goals in the long term. For instance, agriculture policies focusing on resilience could reduce the impacts of climate change/biophysical risk, efficiency could optimise resource use, and equity could reduce social vulnerabilities within the agriculture system for higher productivity.

Moreover, agriculture policies need complete and functioning structures to ensure consistent and timely distribution of resources, including inputs, logistics, funding and services. As shown in the present study, inconsistent and inadequate resources to fulfil agriculture policies impacts the most vulnerable farmers who cannot afford private resources for farming. Poor institutional funding, personnel and logistics allocations to implement policy programmes affect extension services. A solid public-private partnership where the private sector is incentivised with tax exemptions to invest in producing inputs like certified seeds, organic fertilizers and agrochemicals while supporting services like crop insurance, information and loan/credit services to smallholder farmers could help strengthen public policies. However, caution must be taken with solid regulations in such policy developments to prevent total privatisation of the agriculture system, which could make resources expensive and hurt vulnerable farmers the most.

Moreover, implementing efficient resource distribution must go along with policies that achieve equity among social groups within the agriculture system. Identified vulnerable groups in the present study, including women, the less-educated, the elderly and farmers without water sources for dry season farming, must be backed with targeted legislation that ensures that resources and services are allocated without any cultural, political or household power influence or bias. Such legislation could be achieved with participatory and collaborative negotiations between formal and informal institutions at the local and national levels. For instance, women's land ownership hindered by cultural inheritance norms could be negotiated with traditional leaders to allow government legislation to override cultural norms on inheritance. However, negotiations to develop acceptable legislation should be a continuous process with all stakeholders rather than an event since local communities in Northern Ghana are more attached to their cultural norms than government regulations.

8.5.3 Practice contributions

The present study could be helpful for practical application in accessing information, increasing expenditure, adopting efficient on-farm and off-farm strategies, enhancing institutional collaborations and enabling participatory processes. The study showed that access to expert advice or information could improve productivity for farmers. Institutional support to enable smallholder farmers to access relevant and timely information in suitable formats could enable them to make better decisions towards achieving SI goals at the farm and household levels. Information transfer among institutions could enhance institutional capacity and learning, which helps provide better services to farmers. Practical SI information on water, soil, ecosystem and crop-related strategies to farmers could be in the form of radio events, field demonstrations and phone calls. The most vulnerable farmers need information that enables them to adopt efficient strategies that could enhance resilience and productivity, while the more resilient farmers may require information that enhances their sustainable use of resources. Short courses, workshops and seminars could target institutional stakeholders to enhance their capacities for efficient services.

Moreover, the present study showed that increasing expenditure could increase yields and the number of efficient on-farm adoptions. Institutional support will be required to enhance wealth creation opportunities among smallholder farmers, such as VSLAs, off-farm activities and commercial farming. VSLAs may need extra funding support to lend more loans than they saved, especially to vulnerable farmers, enabling them to access resources to engage in productive farming. Commercial farming must be encouraged among farmers, especially in RVB, to provide supplementary incomes to support household food security. Tree crops like cashew could enable farmers to practice agroforestry, where household food crops are cultivated alongside cash crops.

Additionally, the study showed that farmers with water sources were more likely to increase yields than those without in both basins. Farmers without water sources could be trained on water harvesting techniques such as Zai pits and half-moon as farm-level strategies, while small dams, boreholes and dugouts could be constructed as community-level water management projects for dry season irrigation farming. Alternatively, communities without water sources and those with higher migration rates could be supported with alternative livelihood sources such as livestock rearing, craftmanship and food processing during the dry season.

Again, local institutions must find various means of enhancing the collaborations that could enable access to resources, including funding, personnel and logistics, to provide efficient services to farmers. The present study showed that most institutional constraints could be adequately addressed with institutional collaborations and partnerships, especially the most challenging constraints in BVB. Institutional visits, collaborative projects and joint proposals for funding, especially between government and non-government agencies, could help increase the capacity for both institutional stakeholders and farmers. National and international donors for local implementation activities must ensure project funding is based on collaboration and partnerships across diverse institutions.

Lastly, participatory processes must involve all relevant stakeholders and social groups when conducting research, implementation actions and policy formulation activities. Making sure that all voices within the agriculture system are heard and involved could provide a holistic assessment or implementation of projects and policies. For instance, the voices of the most vulnerable, often not considered due to household/community power dynamics, need to be elevated during research, practice or policy activities. These actions could enable an equitable agriculture system that serves social groups' resilience and productivity needs, especially for less-educated older women in BVB.

8.6 Plan for research dissemination

The research findings from the present study will be used for academic and non-academic purposes. The findings will be used for academic purposes to publish at least 3 peer-reviewed articles and 5 external/internal conference presentations within a year. The presentation could be in the form of a poster presentation, paper discussions and an online or in-person presentation. The non-academic dissemination will include Twitter posts, blogs, webinars, newspaper articles and possible local radio discussions. The research will leverage previous experience as a social media manager to create a unique Twitter handle and collaborate with others to target critical stakeholders and institutions in Ghana who could benefit from these findings. A few blog posts will be created to share critical findings of the study and the PhD journey experiences to help other researchers and postgrad students who intend to do fieldwork or similar studies.

Furthermore, the researcher hopes to leverage an existing network with local and national stakeholders in Ghana to organize a webinar that will share the study's findings and get feedback on any missing information that could be added for future research. The existing network will be used to collaborate with a known national online and print media in Ghana to publish two news articles around the findings to grasp attention for the study's policy and practice recommendations.

Finally, the study hopes to seek funding to organise a feedback session to present data and results to the community. This feedback session will be done by engaging with a local radio station and some institutions in the case study areas for an in-person or four-session radio event to discuss the study findings with farming communities. These radio events have the potential to reach thousands of farmers who may need the information to improve their farming activities.

8.7 Summary

This chapter described how the research findings contributed to the aim of the study, indicating that the water/soils risks, access to agriculture resources, demographic characteristics, institutional collaboration and household production needs are the differentiating productivity determinants between and within RVB and BVB that could enable or hinder SI goals in semi-arid Northern Ghana. The study contributed to existing SI knowledge on productivity goals, the SI framework as a guiding principle, input intensification for productivity, trade-offs within the SI practice and SI methodological framework. However, the present study was limited by its scope, short timelines, narrow agriculture perspective and selective methodology. General productivity, resource management, and equity recommendations enabling SI goals were presented for future research, policy, and practice contributions.

As smallholder farmers in semi-arid Northern struggle to hold onto their farming livelihoods due to multiple risks challenging their food systems, the study provides some guiding principles that could reduce risks, build resilience and enhance productivity for an equitable agriculture system.

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APPENDICES

Appendix A: Ethical Clearance approval for fieldwork activities.

UNIVERSITY OF CAPE TOWN
IYUNIVESITHI YASEKAPA • UNIVERSITEIT VAN KAAPSTAD

Faculty of Science
University of Cape Town
Rondebosch
South Africa 7701

E-mail: shari.daya@uct.ac.za
Tel: 021 650-2880

8 October 2019

Mr. Prince Ansah
Environmental and Geographical Science

RE: Is Sustainable Intensification Possible in West Africa? The case of the Volta Basin in Semi-arid Ghana.

Dear Mr. Prince Ansah

I am pleased to inform you that the Faculty of Science Research Ethics Committee has approved the above-named application for research ethics clearance, subject to the conditions listed below.

- Implement the measures described in your application to ensure that the process of your research is ethically sound; and
- Uphold ethical principles throughout all stages of the research, responding appropriately to unanticipated issues: please contact me if you need advice on ethical issues that arise.

Your approval code is: **FSREC 93 - 2019**

I wish you success in your research.

Yours sincerely

Dr Shari Daya
Chair: Faculty of Science Research Ethics Committee

cc. Dr. Marieke Norton (supervisors)

Appendix B: Household Questionnaire for field surveys in RVB and BVB

Household Questionnaire

UNIVERSITY OF CAPE TOWN, SOUTH AFRICA
DEPARTMENT OF ENVIRONMENTAL AND GEOGRAPHICAL SCIENCE
AFRICAN CLIMATE AND DEVELOPMENT INITIATIVE

The Household Questionnaire

Questionnaire ID:			**Date**:
District:		**Community**:	**Basin:**
GPS coordinates:	X:	Y:	**Altitude:**
Name of enumerator:			
Time:			

Please, tick (√) in the brackets [ ] and write at the appropriate space provided. Thank you.

SECTION A

Background Information of Respondent

Q1 Gender: a). Male [ ] b). Female [ ]

Q2 Age group: a). Less than 20 years [ ] b). 20-29 years [ ] c). 30-39 years [ ] d). 40-49 years [ ] e). 50 years and above [ ]

Q3 Level of Education: a). Primary [ ] b). JSS/Middle School [ ] c). Non Formal Education [ ] d).Secondary/Vocational/Technical [ ] e). Tertiary [ ] f). None [ ]

Q4 Marital Status: a). Single [ ] b).Married [ ] c).Divorced/Separated [ ] d).Widowed [ ]

Q5 Are you the head of the household? a). Yes [ ] b). No [ ]

Q6 How many persons are currently living in your household? a). Total ……. b). No. of Males….. c). Female……. d). No. of persons below 18 years…………

Q7 What is the major occupation of your household? a). Farming [ ] b). Formal employment [ ] c). Trading [ ] d). Labour work [ ] Others (specify)..

Q8 How long have you been farming? a). less than 2 years [ ] b). 2-5 years [ ] c). 6-10 years [ ] d). 11-15 years [ ] e). 16 years and above [ ]

Q9 Are you from this community? a). Yes [ ] b). No [ ]

Q10 What is your farm size? a). <2 acre [ ] b). 2-4 acre [ ] c). 5-7 acre [ ] d). 8-10 acre [ ] e). More than 10 acres [ ]

What is the nature of farmland acquisition? a). Family [ ] b). Rental [ ] c). Landlord [ ] d).

Q12 Sharecropping [ ] e). Others (specify) …………

SECTION B

Biophysical Characteristics of Respondent's Farm

Q13 Please, indicate the observed occurrence or availability of the following biophysical/natural resources on your farm for the past 2 to 5 farming seasons.
(***Use 1 to 5***)

Biophysical characteristics for crop production ***(Biophysical indicators as identified by stakeholders in the Volta basin)***	***1= very low, 2= Low, 3= Medium, 4= High and 5= Very high***				
	1	**2**	**3**	**4**	**5**
Unreliable rainfall over farming seasons					
Change in the start of planting dates					
Increased temperature over farming seasons					
Frequent dry spells over farming seasons					
Severe floods over farming seasons					
Scarce water resources (irrigation/water sources) for crop production					
Limited soil water/moisture over the farming seasons					
Depleted soil nutrient/fertility					
Poor soil organic matter content					
Occurrence of pest infestation on crops					
Occurrence of disease infestation on crops					
Occurrence of bushfires on farms					
Tress cutting for charcoal/firewood on farm over					
Occurrence of erosion on farm					
Depletion tree cover on farm					

SECTION C

Farming practices/strategies that ensure efficiency for maintaining biophysical/natural properties for higher productivity

Q14 Please indicate whether your household has adopted any of the strategies/farm practices listed below (Use 1 to 3 for Q14 and Q16 and 1 to 5 for Q15 and Q17)

Farm strategies/practices	Have adopted this strategy?	**Q15** if yes, how effective is this practice?	**Q16** Do you follow extension service advice in the use of this practice?	**Q17** If no, why not?
	1. Yes 2. No	1. Very ineffective 2. Ineffective 3. Medium 4. Effective 5. Very effective	1. Yes 2. No	1. Cost 2. Not known 3. Not sufficient information 4.Uncertain outcome 5. Not enough
1. Growing improved seeds				
2. Seed testing before sowing				
3. Practice planting guidelines (sowing in rows, crop concentration)				
4. Practicing mixed cropping (growing different crops together)				
5. Crop rotation with legumes				
6. Mulching (covering the soil to keep in moisture)				
7. Water harvesting (collecting rainwater for irrigation)				
8. Practicing irrigation (with nearby water sources or groundwater).				
9. Land preparation (Tillage/ploughing)				
10. Using chemical fertilisers (NPK 60-60-60)				
11. Using leguminous crops (cowpea, beans)				
12. Using organic manure (compost, animal droppings)				
13. Pest/Disease control practices (pesticides, weedicide)				
14. Erosion control (terracing, contour bands)				

SECTION D

Productivity levels (crops, income and food security) of smallholder farmer households

Q15 Please provide with accurate recollection of production activities for 2 major crops grown for the previous season (Use Q15 to Q20)

Major crops produced	**Q16** Land size Cultivated (acres)	**Q17** Expected yields (kg)	**Q18** Actual yields (kg)	**Q1**9 Yield sold	**Q20** Yield consumed	**Q21** Yield used for other purposes (loan payment, funeral, etc

Q22 Kindly provide with accurate recollection the amount spent/received for farming activities for the previous season (Use Q22 to Q27)

Amount spent/received from farming activities	Amount in GH	How do you consider this amount compared to previous seasons? 1. Very Low 2. Low 3. Medium/Normal 4. High 5. Very High
Q22 Expenditure on crop production		
Q23 Income from crop production		
Q24 Income from off-farm activities		
Q25 Household savings		
Q26 Loan amount received		
Q27 Remittances		

Q27 How profitable is agriculture to your household? 1) Very unprofitable [ ] 2) Unprofitable [ ] 3) Average [ ] 4) Profitable [ ] 5) Very profitable [ ]

Q28 Please provide accurate recall in months for your household food security needs for the previous farming season (Use Q28 to Q30)

Household food security	No. of months	How do you consider this amount compared to previous seasons? 1. Very Low 2. Low 3. Medium 4. High 5. Very High
Q28 Food availability		
Q29 Food access		
Q30 Food sufficiency		

SECTION E

Household socioeconomic activities that support sustainable intensification

Q31 How many off-farm income-generating activities are the members of your household engaged in?

a). None [ ] b). One [ ] c). Two [ ] d). Three [ ] e). Four or more [ ]

Q32 If any, what is the most relevant off-farm income-generating activity for households?

a). Petty Trading [ ] b). Food processing [ ] c). Handicraft [ ] d). Labour e). Other [ ]

Q33 Do you belong to any farmer-based organisation (FBO)? a). Yes [ ] b). No [ ]

Q34 If 'yes', how beneficial is FBO to your farming productivity? a). Not beneficial [ ] b). Little beneficial [ ] c). Beneficial [ ] d). Very Beneficial [ ]

Q35 How many persons are required for labour on your farmland? Total… No. of Males…. |No. of Female……

Q36 Please indicate whether your household have access to the following farm inputs and services? (Q36 to 39)

Farm inputs	Do you have access to this input?	**Q37** if no, why?	**Q38** If yes, who largely provide this this inputs/service?	**Q39** How often do you have access to this input/service?
	1. Yes 2. No	1. Cost 2. Not available 3. Limited supply 4. Inadequate information 5. Other	1. NGO 2. Gov't programme 3. Private sector 4. Friends/Family 5. Others	1. Never 2. Not often 3. Average 4. Often 5. Very often
1. Fertilizer				
2. Improved seeds				
3. Pesticides				
4. Farm tools				
5. Machinery (Tractor service)				
6. Credit				
7. Information (Weather)				
8. Insurance				
9. Land				
10. Storage				
11. Extension services				
12. Market				

Q40 Please indicate how your household assets contribute to farm productivity?

Household assets	Do you own this assert? 1. Yes 2. No	**Q41** If yes, how beneficial is this assert to productivity? 1. Never 2. Little beneficial 3. Medium 4. Beneficial 5. Very beneficial
1. Radio		
2. TV		
3. Mobile phone		
4. Internet		
5. Car/Motorcycle		
6. Electricity/Energy		

Q42 How often do you try new technology on your farm or household? a). Never [ ] b). Not often [ ] c). Often [ ] d). Very often [ ]

Q43 How many new technologies have you tried in the past year? a). 1 [ ] b). 2 [ ] c). 3 [ ] d). 4 [ ] e) 5 or more [ ]

SECTION F

Household recovery from social and economic for sustainable intensification

Q44 How often have you had conflicts over farm resources (including water, land, crops, and inputs)? a). Never [ ] b). Not often [ ] c). Often d). Very Often

Q45 If you have had conflicts over resources who and how was its resolved?
....
....

Q46 How effective were the conflicts over resources resolved? a). Never [ ] b). Not effective [ ] c). Effective [ ] d). Very effective [ ]

Q47 How frequently do members of your household migrate to other places for work? a). Never [ ] b). Not frequently [ ] c). Frequently [ ] d). Very Frequently [ ]

Q48 How beneficial is migration to your farming activities and household? a). Never [ ] b). Not beneficial [ ] c). Beneficial [ ] d). Very beneficial [ ], If Never explain why…………………………………...

Q49 What is your response to an unfavourable market (including low prices, poor sales) ?
……

Q50 Do you have any reliable support system during food/financial crisis? a). Yes [ ] b). No [ ]

Q51 If yes, who provide this support? a). NGO [ ] b). Gov't programme [ ] c). Private sector [ ] d). Friends/Family [ ] e). Others………………

Q52 Is there any other factor (s) you perceive hinder your ability to increase productivity and maintain natural resources?
....

Thank you.

Appendix C: KII and FGD guide

Appendix C(i): Interview guide for focus group discussion in RVB and BVB.

Questions for Focus group Discussions

Basin
Community
Number of participants
Social group

1. How do you perceive the pattern of rainfall lately (for the past 5 – 10 years) now?
    - How does the observed pattern affect farming activities?
    - What do you do when the rain delays?

2. How is your soil condition?
    - What strategies have been useful in improving the soil?
    - Do you practice compost, and how are they made?

3. How have pests and diseases affected your crops?
    - If your farm is 5 acres, how many acres will be destroyed by the pest and diseases?
    - Tell me when you were affected by armyworm; out of 10 acres, how many acres did you get a good yield of food from?

4. How do you get access to fertilisers and agrochemicals?
    - Does it come on time and also is it enough?
    - How many bags do the DOA give each farmer?
    - Does everyone here receive fertiliser from planting for food and jobs for farming? if yes, let me see your hand up.

5. How often do you get agriculture training during the year?
    - Does everybody in the community get to be trained?
    - When trained, do you put it to practice?

6. How do you receive your information?
    - How many of you present have radios?

7. How many of us have participated in migration and why?
    - Is it good to travel out and leave your agriculture behind?
    - Explain whether migration is good or not for farming?

8. What are the key problems affecting farming in this locality?
    - How do you store your crops, and is the method effective?
    - How long (in months) do harvested yields last before the next season?

9. In a case where that time there is no food, what happens?

10. How many of you here do other jobs apart from farming?
    - What type of work livelihood options beside farming do people engage in?

11. How do you market your produce after harvest?

Appendix C(ii): Interview guide for key informant interviews in RVB and BVB.

Key Informant Interview Guide

INTERVIEW SCHEDULE FOR INSTITUTIONAL KEY INFORMANTS AND STAKEHOLDERS

This interview is a follow-up to a workshop conducted with key stakeholders in the Upper West and Upper East regions on their key constraints towards implementing sustainable intensification. The questions are based on the results from the workshop that require further detailed information.

Section A
Background characteristics

1. Name of Officer/respondent…………………………………………………………………...............

2. Unit/Department……………………………………… 3. Designation/Rank…………………………

4. Educational background …………….…………………… 5. Gender……………………………

6. No. of years at post……………………………………………………………………………………

Section B
Stakeholder constraints for the implementation of Sustainable intensification

Q1. What policies or programmes (at the local/regional/national) are you aware of that support your work in the following areas?

- High crop productivity………………………………………………………………………
- Maintaining natural resources (water, soils and forest) ....
- Individual wellbeing……………………………………………………………………….
- Women empowerment……………………………………………………………….......

Q2. How do you perceive the effectiveness of agriculture policy and programme implementation in the following areas: rate from 1 to 5, with 1 as "Not effective" and 5 as "very effective"? Explain your answer

- Research………………………………………………………………..
- Extension……………………………………………………………
- Training and education……………………………………………..
- Input supply………………………………………………………..
- Markets………………………………………………………………..

Q3. In what ways do or could the following areas of instability affect your work with communities?

- Environmental instability (erratic rainfall, bushfires, deforestation) ………………………..
- Social instability (conflicts over resources) …………………………………………………
- Economic instability (poverty, poor markets for crops) …………………………………….

Q4. Why are many constraints affecting your work to support sustainable intensification emerging equally from the following administrative levels?

- Local level (community/village/town) ………………………………………………………
- National level……………………………………………………………………………..

Q5. Under structural conditions, why do you perceive institutions are responsible for about 60% of the overall constraints for sustainable intensification in the region?

Q6. In what ways does inadequate collaboration and interaction among stakeholders hinder the progress of sustainable intensification? Please provide examples……………………………………………………..

Q7. Why are irregular community meetings a key constraint for sustainable intensification implementation?

- How are these meetings arranged or organised? ……………………………………………

Section C

Solutions to address stakeholder constraints for the implementation of Sustainable intensification

Q8. Where do farmers in the region generally get their information from?

Q9. What knowledge does your institution generate and share with the following stakeholders?

- Farmers……………………………………………………………
- Private…………………………………………………………..
- Government institutions…………………………………………..

Q10. What channels do you use to generate and share the information with these stakeholders?

- Farmers……………………………………………………………
- Private…………………………………………………………..
- Government institutions…………………………………………..

Q11. What information or knowledge do you need to support your work, and who do you think can provide this information?

Q12. What role does your institution play in maintaining and regulating the use of natural resources?

- Water resources………………………………………………………………………..
- Soils……………………………………………………………………………………
- Forest and biodiversity………………………………………………………………………

Q13. What structures do you have in place to address the constraints you face in your institution to implement sustainable intensification?

Q14. Which institution or organisation do you think your institutions can collaborate with to address your constraints and efficiently implement sustainable intensification? Kindly explain your answer…………..

Q15. What tools do you use for collaboration and interaction with other institutions/stakeholders? Which tool is the most efficient tool and why?

Q16. Why are 60% of stakeholder constraints difficult to solve? (Only for Black Volta Basin). Why are 72% of stakeholder constraints easy to solve? (Only for White Volta Basin).

Q17. What innovation does your organisation have or is engaged in that supports the following?

- High crop productivity…………………………………………………………………
- Maintaining natural resources (water, soils, and forest) ....
- Individual wellbeing……………………………………………………………………..
- Women empowerment……………………………………………………………......

THANK YOU

Appendix C(iii): Consent forms for survey, FDG and KII in RVB and BVB.

Survey Participant Consent Form

Research Title: Is Sustainable Intensification possible in Smallholder Crop Production Systems in Semi-Arid West Africa? The Case of the Red Volta and Black Volta Basins in Northern Ghana.

Dear Participant,

You are invited to participate in a survey as part of a PhD research study. Before you decide to participate, please read the following information:

1. **Purpose:** The purpose of this survey is to determine the factors contributing to productivity differences between RVB and BVB and how these factors could influence the implementation of SI within smallholder agriculture systems in semi-arid Northern Ghana.
2. **Procedure:** You will be asked to answer a series of questions related to your farming, livelihood activities, yields, incomes and household.
3. **Confidentiality:** Your responses will remain confidential and will be used only for research purposes.
4. **Duration:** The survey will take approximately 60 – 120 minutes to complete.
5. **Risks and Benefits:** There are no known risks associated with this survey, and no direct benefits will be provided.
6. **Voluntary Participation:** Participation in this survey is voluntary. You can withdraw at any time without any consequences.

Consent: I understand the above information and agree to participate in this survey. I understand that I can consent by:

- Signing below
- Providing an audio recording of my consent

Signature: _____________________________ Date: ____________

Focus Group Discussion (FGD) Consent Form

Research Title: Is Sustainable Intensification possible in Smallholder Crop Production Systems in Semi-Arid West Africa? The Case of the Red Volta and Black Volta Basins in Northern Ghana.

Dear Participant,

You are invited to participate in a Focus Group Discussion (FGD) as part of a PhD research study. Please consider the following:

Purpose: The FGD aims to gather collective insights on the factors contributing to productivity differences between RVB and BVB and how these factors could influence the implementation of SI within smallholder agriculture systems in semi-arid Northern Ghana.

Procedure: You will engage in a group discussion with other participants about your farming, livelihood activities, yields, incomes and household.

Confidentiality: The discussion will be recorded, but your identity will remain confidential.

Duration: The FGD will last approximately 45 to 90 minutes.

Risks and Benefits: There are no known risks, and no direct benefits will be provided.

Voluntary Participation: Your participation is voluntary, and you can leave the discussion at any point.

Consent:

I have read the above information and agree to participate in the FGD. I understand that I can consent by:

Signing below

Providing an audio recording of my consent

Signature: ______________________________ Date: _____________

Key Informant Interview Consent Form

Research Title: Is Sustainable Intensification possible in Smallholder Crop Production Systems in Semi-Arid West Africa? The Case of the Red Volta and Black Volta Basins in Northern Ghana.

Dear Sir/Madame,

You have been selected as a key informant for a PhD research study. Before the interview, please note:

Purpose: The interview seeks to gather in-depth information on the factors contributing to productivity differences between RVB and BVB and how these factors could influence the implementation of SI within smallholder agriculture systems in semi-arid Northern Ghana.

Procedure: You will be interviewed by the researcher on topics related to the challenges and opportunities you encounter in executing your work in support of farmers.

Confidentiality: The interview will be recorded, but your identity and responses will remain confidential.

Duration: The interview will take approximately 30 – 60 minutes.

Risks and Benefits: There are no known risks, and no direct benefits will be provided.

Voluntary Participation: Your participation is entirely voluntary, and you can end the interview at any time.

Consent:

I have understood the information provided and agree to participate in the interview. I understand that I can consent by:

Signing below

Providing an audio recording of my consent

Signature: ______________________________ Date: _____________

Appendix D: Supplementary information from chapter 3

Appendix D (i): The types of associations, the questions asked, and the test conducted for the results and analysis section for objective 1

Sections		Type of associations	Questions asked from the dataset
Results	*Biophysical risks perception*	Pearson's Chi-square (χ^2) tests whether the frequency of perceived biophysical risks differs between RVB and BVB.	*Is the pattern of ranked biophysical risks perceived differently between basins?*
		Pearson's t-test tests the differences in means for average ranked water, soil, ecosystem and crop health risk perceptions between RVB and BVB.	*Is the mean average rank for water, soil, ecosystem, or crop health risks perceived differently between basins?*
		Pearson's Chi-square (χ^2) tests whether the frequency of adopted on-farm differs between RVB and BVB.	*Is the pattern of adopted on-farm strategies to respond to biophysical risks different between basins?*
	On-farm strategies (Adoption, effectiveness, and expert advisory)	Pearson's t-test tests the mean differences for the number of adopted on-farm strategies between *RVB and BVB*.	*Are the number of adopted on-farm strategies different between basins?*
		Pearson's Chi-square ($\chi 2$) tests whether the frequency of perceived effectiveness of on-farm strategies differs between *RVB and BVB*.	*Is the pattern of ranked perception of the effectiveness of on-farm strategies different between basins?*
		Pearson's t-test tests the differences in means for the average rank effectiveness of on-farm strategies between *RVB and BVB*.	*Is the mean average rank effectiveness of on-farm strategies perceived differently between basins?*
		Pearson's Chi-square ($\chi 2$) tests whether the frequency of expert advisories on on-farm strategies differs between RVB and BVB.	*Is the pattern of expert advisories on on-farm strategies different between basins?*
		Pearson's Chi-square ($\chi 2$) tests whether the frequency of the reasons for not adopting on-farm strategies differs between RVB and BVB.	*Is the pattern of the reasons for not adopting on-farm strategies different between basins?*
Analysis	*Empirical analysis of biophysical risks perception*	Spearman's correlation tests whether the overall average biophysical risk perception has a positive or negative effect on productivity levels in RVB and BVB.	*Do the averaged rank biophysical risk perceptions increase or decrease with expected and actual crop yields within basins?*
		Multiple linear regression tests whether expected or actual crop yield levels could predict the overall average biophysical risk perception in RVB and BVB.	*Can the average rank biophysical risk perception be influenced by expected and actual crop yield levels within basins?*
		Stepwise regression tests which perceived biophysical risks can predict crop yield levels in RVB and BVB.	*What perceived biophysical risks could influence crop yield levels within basins?*
		Pearson's Chi-square (χ^2) tests whether the frequency of perceived biophysical risks differs with respondents' demographic background in RVB and BVB.	*Is the pattern of ranked biophysical risks perceived differently based on respondents' communities, genders, age groups and educational levels within basins?*
		Pearson's t-test tests the differences in means for the average rank water, soil, ecosystem and crop health risk perception and respondents' communities in RVB and BVB.	*Is the mean average rank for water or soil or ecosystem, or crop health risks perceived differently in communities within basins?*
		Pearson's Chi-square (χ^2) tests whether the frequency of perceived biophysical risks differs with access to extension and information in RVB and BVB.	*Is the pattern of ranked biophysical risks perceived differently based on access to agriculture extension and information within basins?*
		Pearson's t-test tests the differences in means for the average rank water, soil, ecosystem and crop health risk perception and access to extension and information in RVB and BVB.	*Do access to agriculture extension and information determine how respondents perceive overall water, soil, ecosystem, and crop health-related risks in RVB and BVB?*
		Binary logistic regression tests whether access to agriculture extension could predict access to information in RVB and BVB.	*Can access to agriculture extension influence access to information in RVB and BVB?*

		Multiple linear regression tests whether farm size, expected yields, number of inputs/services, and expenditure could predict the overall average biophysical risk perception in RVB and BVB.	*Can the average rank biophysical risk perception be influenced by farm size, expected yields/ha, number of inputs/services, and expenditure within basins?*
	Empirical analysis of On-farm strategies (Adoption, effectiveness, and expert advisory)	Spearman's correlation tests whether the number of adopted on-farm strategies has a positive or negative effect on productivity levels in RVB and BVB.	*Do the number of adopted on-farm strategies increase or decrease with expected and actual crop yields within basins?*
		Stepwise regression tests which adopted on-farm strategies can predict crop yield levels in RVB and BVB.	*Which adopted on-farm strategies could better influence crop yield levels within basins?*
		Pearson's Chi-square (χ^2) tests whether the frequency adopted on-farm strategies differs with respondents' demographic background in RVB and BVB.	*Is the pattern of adopted on-farm strategies different based on respondents' communities, genders, age groups and educational levels within basins?*
		Pearson's t-test tests the differences in means for the number of adopted on-farm strategies and respondents' demographic backgrounds in RVB and BVB.	*Are the number of adopted on-farm strategies different based on respondents' communities, genders, age groups and educational levels within basins?*
		Multiple linear regression tests whether farm size, number of inputs/services, expenditure, and yield levels (expected and actual) could predict the number of adopted on-farm strategies in RVB and BVB.	*Can the number of adopted on-farm strategies be determined by including farmland size, number of inputs/services, expenditure, expected yields/ha and actual yields/ha within basins?*
		Pearson's correlation tests whether the number of adopted on-farm strategies has a positive or negative effect on the overall average biophysical risk perception in RVB and BVB.	*Does the number of adopted on-farm strategies increases or decrease with the average ranked biophysical risk perceptions within basins?*
		Pearson's Chi-square (χ^2) tests whether the frequency adopted on-farm strategies differs from perceived biophysical risks in RVB and BVB.	*Is the pattern of adopted on-farm strategies different based on ranked biophysical risk perceptions within basins?*
		Binary logistic regression tests whether perceived biophysical risks could predict adopted on-farm strategies in RVB and BVB.	*Which relevant biophysical risk perceptions could better predict adopted on-farm strategies within basins?*
		Multiple linear regression tests whether access to agriculture advisory, information, extension and FBO could predict the number of adopted on-farm strategies in RVB and BVB.	*Can the number of accesses to agriculture advisory, information, extension and FBO predict the number of adopted on-farm strategies within basins?*
		Multiple linear regression tests whether expected and actual yield levels could predict the average ranked effectiveness of on-farm strategies in RVB and BVB.	*Can the average ranked effectiveness of adopted on-farm strategies determine the expected and actual yields with basins?*
		Binary logistic regression tests whether access to and respondents' access to extension, information, FBO, radio and mobile phone could predict access to expert advisory in RVB and BVB.	*Can respondents' access to extension, information, FBO, radio, and mobile phone determine their access to expert advisories within basins?*
		Pearson's t-test tests the differences in means for the number of expert advisories received differs with the number of accesses to extension, information, FBO, radio and mobile phone in RVB and BVB.	*Are the average number of expert advisories received differently based on the number of accesses to extension, information, FBO, radio, and mobile phone within basins?*
		Pearson's Chi-square (χ^2) tests whether the frequency of expert advisories differs from on-farm adoptions and the effective on-farm adoptions in RVB and BVB.	*Is the pattern of expert advisories received differently based on adopted on-farm strategies and their perceived effectiveness within basins?*

Appendix D (ii): The types of associations, the questions asked, and the test conducted for the results and analysis sections for objective 2.

	Sections	**Type of association**	***Questions asked from the dataset***
Results	*Crop type and cultivated cropland*	Pearson's Chi-square (χ2) tests whether the frequency of crop types differs between RVB and BVB.	*Is the pattern of crop types different between basins?*
		Pearson's Chi-square (χ2) tests whether the frequency of cropland acquisition differs between RVB and BVB.	*Is the pattern of access to cropland different between basins?*
		Mann-Whitney U tests whether the total cropland sizes differ between RVB and BVB.	*Are the total cropland different between basins?*
		Mann-Whitney U tests whether the cropland sizes for dominant crops differ between RVB and BVB.	*Are the cropland for primary and secondary crops different between basins?*
	Crop production outcomes	Mann-Whitney U tests whether the expected crop yield levels differ between RVB and BVB.	*Are the expected primary and secondary crop yield/ha levels different between basins?*
		Mann-Whitney U tests whether the actual crop yield levels differ between RVB and BVB.	*Are the actual primary and secondary crop yield/ha levels different between basins?*
		Mann-Whitney U tests whether the crop yield levels consumed differ between RVB and BVB.	*Are consumed primary and secondary crop yield/ha levels different between basins?*
		Mann-Whitney U tests whether the crop yield levels sold differ between RVB and BVB.	*Are sold primary and secondary crop yield/ha levels different between basins?*
		Mann-Whitney U tests whether the crop yield level for other purposes differ between RVB and BVB.	*Are primary and secondary crop yield/ha levels for other purposes different between basins?*
		Simple linear regression tests whether the total actual crop levels can predict the total yield consumed and total yield sold in RVB and BVB.	*Can respondents' total actual yield/ha levels determine yield/ha levels consumed and sold within basins?*
	Economic characteristics and outcomes	Mann-Whitney U tests whether total farm expenditure differ between RVB and BVB.	*Are the amount spent (GH/ha) on crop production different between basins?*
		Mann-Whitney U tests whether total crop yield income differ between RVB and BVB.	*Are the amount received (GH/ha) on crop yields sold different between basins?*
		Mann-Whitney U tests whether total profits or loss from crop yields sold differ between RVB and BVB.	*Are profits or losses (GH/ha) made on crop yield sold different between basins?*
		Mann-Whitney U tests whether total off-farm income differ between RVB and BVB.	*Are the amount (GH/ha) received as off-farm incomes (remittances and alternative livelihood incomes) different between basins?*
		Mann-Whitney U tests whether total savings and loans amount differ between RVB and BVB.	*Are savings and loans (GH/ha) made different between basins?*
	Social characteristics	Pearson's Chi-square (χ2) tests whether the frequency of participation in off-farm activities (alternative livelihood and migration) differs between RVB and BVB.	*Is the pattern of engagement in alternative livelihood activities different between basins?*
			Is the pattern and frequency of migration different between basins?
		Pearson's Chi-square (χ2) tests whether the frequency of participation in FBO differs between RVB and BVB.	*Is the pattern of engagement in FBO activities and their benefits different between basins?*
		Pearson's Chi-square (χ2) tests whether the frequency of input access differs between RVB and BVB.	*Is the pattern of access to inputs (including fertilisers, improved seeds, pesticides, farm tools and land) different between basins?*
		Pearson's Chi-square (χ2) tests whether the frequency of access to services differs between RVB and BVB.	*Is the pattern of access to services (tractor use, credit, information, storage, market opportunities and extension) different between basins?*
Analysis	*Determinants of crop production outcomes*	Kruskal-Wallis H tests whether total crop yield levels (actual and expected) differ with communities in RVB and BVB.	*Are the expected and actual crop yield/ha levels different for communities within basins?*
		Mann-Whitney U tests whether total crop yield levels (actual and expected) differ with respondents' demographic backgrounds in RVB and BVB.	*Are the expected and actual crop yield/ha levels different for respondents' age, gender, and education within basins?*
		Mann-Whitney U tests whether total crop yield levels (actual and expected) differ with access to FBO and extension services in RVB and BVB.	*Are the expected and actual crop yield/ha levels different for accesses to FBO and extension services within basins?*

		Simple linear regression tests whether the total yield levels (actual and expected) can be predicted by farm expenditure in RVB and BVB.	*Can the total farm expenditure determine the expected and actual yield/ha levels within basins?*
		Mann-Whitney U tests whether total crop yield levels (actual and expected) differ with access to credit in RVB and BVB.	*Are the expected and actual crop yield/ha levels different for access credit within basins?*
		Spearman's correlation tests whether the number of inputs/services accessed has a positive or negative effect on yield levels (actual and expected) in RVB and BVB.	*Does the number of* inputs/services accessed *increase or decrease with expected and actual crop yields within basins?*
		Stepwise regression tests which inputs or services can predict crop yield levels (actual and expected) in RVB and BVB.	*Which farm inputs or services could better influence expected and actual crop yield/ha levels within basins?*
		Multiple linear regression tests whether the total yield levels (actual and expected) can be predicted by total cropland size in RVB and BVB.	*Can the total cropland size determine the expected and actual yield/ha levels for the primary, secondary and overall yields within basins?*
		Mann-Whitney U tests whether total crop yield levels (consumed and sold) differ with respondents' demographic background in RVB and BVB.	*Are the crop yield levels consumed and sold different for respondents' gender and marital status within basins?*
		Spearman's correlation tests whether the total farm expenditure has a positive or negative effect on crop yield levels (consumed or sold) in RVB and BVB.	*Does farm expenditure increase or decrease with crop yield/ha consumed and sold within basins?*
		Multiple linear regression tests whether the crop yield levels (consumed or sold) can be predicted by farm expenditure in RVB and BVB.	*Can the farm expenditure determine the crop yield levels consumed and sold within basins?*
		Mann-Whitney U tests whether total crop yield levels (consumed and sold) differ with FBO participation in RVB and BVB.	*Are the crop yield levels consumed and sold different for FBO participation within basins?*
	Determinants of cropland ownership/ size	Pearson's Chi-square ($\chi 2$) tests whether the frequency of cropland ownership differs with respondents' demographic background in RVB and BVB.	*Is the pattern of cropland ownership different for respondents' gender, marital status and headship within basins?*
		Spearman's correlation tests whether the total cropland size has a positive or negative effect on household size in RVB and BVB.	*Does the total cropland size increase or decrease with household size within basins?*
	Determinants of economic outcomes/characteristics	Spearman's correlation tests whether total farm expenditure has a positive or negative effect on total crop yield incomes in RVB and BVB.	*Does farm expenditure increase or decrease with crop yield incomes within basins?*
		Spearman's correlation tests whether total farm expenditure has a positive or negative effect on profits/losses in RVB and BVB.	*Does farm expenditure increase or decrease with farm profits/losses within basins?*
		Spearman's correlation tests whether total crop yield incomes have a positive or negative effect on profits/losses in RVB and BVB.	*Does crop yield income increase or decrease with farm profits/losses within basins?*
		Multiple linear regression tests whether total farm expenditure and yield incomes can predict by yield profits/losses in RVB and BVB.	*Can the farm expenditure and yield income determine the crop yield profits/losses within basins?*
		Mann-Whitney U tests whether the mean ranks economic outcomes (expenditure, income, and profit/losses differ with respondents' demographic background in RVB and BVB.	*Are the total expenditure, incomes and profits/losses different for respondents' gender, age and education within basins?*
		Mann-Whitney U tests whether the mean ranks economic outcomes (expenditure, income, and profit/losses differ with access to FBOs and extension services in RVB and BVB.	*Are the total expenditure, incomes and profits/losses different for accesses to FBOs and extension services within basins?*

		Kruskal-Wallis H tests whether the mean ranks off-farm incomes (alternative livelihood income and remittances) differ with respondents' communities in RVB and BVB.	*Are the alternative livelihood incomes and remittances different for respondents' communities within basins?*
		Mann-Whitney U tests whether the mean ranks off-farm incomes (alternative livelihood income and remittances) differ with respondents' gender and education in RVB and BVB.	*Are the alternative livelihood incomes and remittances different for respondents' gender and education within basins?*
		Multiple linear regression tests whether total farm expenditure can be predicted by savings and loan amounts in RVB and BVB.	*Can savings and loan amounts predict farm expenditure within basins?*
	Determinants of social characteristics	Spearman's correlation tests whether household size has a positive or negative effect on the number of alternative livelihood activities in RVB and BVB.	*Does household size increase or decrease with the number of alternative livelihood options within basins?*
		Pearson's Chi-square ($\chi 2$) tests whether the frequency of alternative livelihood types differs with respondents' demographic background in RVB and BVB.	*Is the pattern of alternative livelihood activities different for respondents' gender and education within basins?*
		Pearson's Chi-square ($\chi 2$) tests whether migration frequency and benefits differ with respondents' demographic background in RVB and BVB.	*Are the migration pattern and its benefits different for respondents' gender, age and education within basins?*
		Pearson's Chi-square ($\chi 2$) tests whether the frequency of FBO participation differs with access to inputs and services in RVB and BVB.	*Is the pattern of FBO participation different for access to inputs and services within basins?*
		Pearson's Chi-square ($\chi 2$) tests whether access to inputs differs with respondents' demographic background in RVB and BVB.	*Is the pattern of input access different based on respondents' community, gender, and education within basins?*
		Pearson's Chi-square ($\chi 2$) tests whether access to services differs with respondents' demographic background in RVB and BVB.	*Is the pattern of service access different based on respondents' community, gender, and education within basins?*

Appendix D (iii): Theoretical Basis for Using Regression Analysis

The following are the regression models used in the research:

1. Simple Linear Regression (Collis & Hussey, 2014, p. 281 - 282)

Simple regression, also known as simple linear regression, is used when there is a single independent variable. The primary aim is to determine the relationship between the independent variable and the dependent variable. Theoretically, it assumes a linear relationship between the two variables, and it is represented by the equation:

[Y = a + bX]

Where:

• (Y) is the dependent variable

• (X) is the independent variable

• (a) is the intercept

• (b) is the slope of the line

Assumption: Linearity - The relationship between the independent variable X and the dependent variable Y is linear.

Test: Scatter plot of residuals vs. predicted values. If there's a clear pattern (example, a curve), the linearity assumption might be violated.

2. Multiple Linear Regression (Collis & Hussey, 2014, p. 282 - 283)

Multiple regression extends the simple regression by including two or more independent variables. This method allows for the examination of the effects of multiple predictors on the dependent variable. Theoretically, it can capture more complex relationships and interactions between variables. The general equation is:

[Y = a + b_1X_1 + b_2X_2 + ... + b_nX_n]

Assumption: No multicollinearity - Independent variables are not too highly correlated with each other.

Test: Variance Inflation Factor (VIF). A VIF value greater than 10 is usually considered as an indication of multicollinearity.

3. Logistic Regression (Collis & Hussey, 2014, p. 283 - 287)

Logistic regression is used when the dependent variable is categorical, typically binary (e.g., yes/no or 1/0 outcomes). Instead of predicting a continuous outcome, it predicts the probability of an event occurring. Theoretically, it models the log odds of the probability of the event occurring. The logistic function transforms any value into a value between 0 and 1, which can be interpreted as a probability.

The formula for logistic regression is:

$p = 1 / (1 + e^{(-z)})$

where p is the probability of the dependent variable (Y) being equal to 1, e is the base of the natural logarithm (approximately equal to 2.718), and z is the linear combination of the independent variables (X1, X2, ..., Xn) and their coefficients (b1, b2, ..., bn): z = b0 + b1X1 + b2X2 + ... + bnXn

Assumption: Linearity of log odds - The log odds of the outcome is a linear combination of the independent variables.

Test: Box-Tidwell test. This involves creating interaction terms between each independent variable and its natural log and then checking if these interaction terms are significant.

4. Stepwise Regression (Ing & Lai, 2011, p. 3)

Stepwise regression is a method of fitting regression models in which the choice of predictive variables is carried out by an automatic procedure. In each step, a variable is considered for addition to or subtraction from the set of explanatory variables based on some specified criterion. Theoretically, it is used to find the best-fitting model by adding or removing predictors based on their statistical significance.

In the study, we employed stepwise linear regression to identify which climatic risk perception significantly influence actual yield per hectare. The inclusion or exclusion of a variable in the model is determined by an F-test, which tests the null hypothesis that the variable does not significantly improve the model's fit. If the F-value is large enough and the p-value is below the predetermined significance level (0.05), the variable is included in the model.

For example, the variable "perception of increased temperature," had an R-squared value of 0.23. In this case, the F-test was performed to compare a model with this variable to a model without it. The F-value was found to be significant, leading to the inclusion of this variable in the final model. This means that the perception of increased temperature explains approximately 23% of the variance in the actual yield per hectare in the RV. No such variable was found to be significant in the BVB region, as indicated in the results section of the thesis (See Chapter, page 125).

By using the F-test in this manner, we were able to systematically include or exclude variables, thereby arriving at a model that best explains the variability in yield per hectare. This approach ensures that only variables that significantly contribute to explaining the dependent variable are included in the final model.

Assumption: Model specification - The stepwise method, whether forward, backward, or bidirectional, assumes that the model specified is correct at each step.
Test: Check the significance of variables at each step and ensure that the model's Akaike Information Criterion (AIC) or Bayesian Information Criterion (BIC) is improving.

Appendix E: Definitions of technical terms or indicators used in the study.

Appendix E(i): Definitions of biophysical indicators used in the study

#	Indicator	*Definition*
1.	**Erratic rainfall**	*Unpredictable rainfall seasonal rainfall timing*
2.	**Change in planting dates**	*Change in the start of the farming season*
3.	**Increased temperature**	*Increase in perception of heat on crops and farmers*
4.	**Scarce surface water**	*Limited surface water for irrigation in the dry season*
5.	**Scarce groundwater**	*Limited water from wells and boreholes in the dry season*
6.	**Drought**	*Prolonged shortages in the water supply due to low rainfall*
7.	**Dry spells**	*Short periods of water shortages due to low rainfall during the rainy season*
8.	**Water pollution**	*Contamination of water bodies that negatively affect their uses*
9.	**Soil moisture**	*Water content within soil particles*
10.	**Organic matter content**	*any material produced originally by living organisms (plant or animal) that is returned to the soil and goes through the decomposition process*
11.	**Depleted soil nutrients**	*Used-up soil nutrients or observed low soil fertility due to continuous cropping*
12.	**Soil erosion**	*Removal of the topsoil from running water from rainfall*
13.	**Soil stress**	*Pressure applied to the topsoil due to continuous cropping on the same cropland*
14.	**Soil type**	*Well-defined soil properties that share distinctive characteristics*
16.	**Bushfires**	*A fire in scrub or a forest, especially one that spreads rapidly*
17.	**Deforestation**	*Decrease in forest areas that are lost agricultural croplands*
18.	**Waste disposal**	*processes and actions required to manage waste from its inception to its final disposal*
19.	**Pest invasion**	*The sudden increase in destructiveness or population numbers of a pest species in a given area*
20.	**Disease infestation**	*parasitic diseases caused by animals such as arthropods (i.e. mites, ticks, and lice) and worms, including conditions caused by protozoa, fungi, bacteria, and viruses*
21.	**Weed control**	*A control method that aims to prevent weeds from being established in a cultivated crop*
22.	**Irrigation**	*the artificial supply of water to agricultural land for dry season farming*
23.	**Mulching**	*the process of covering the soil surface around the plants to conserve water for the crop growth*
24.	**Water harvesting**	*Collecting rainfall-generated runoff from a particular area (a catchment) provides water for crop use*
25.	**Improved seeds**	*Increasing the quality of seeds that can increase crop yields in less suitable areas crop by significant folds*
26.	**Cover crops**	*Crops grown for the protection and enrichment of the soil*
27.	**Water withdrawals**	*Freshwater taken from ground or surface water sources, either permanently or temporarily, for crop use*
28.	**Crop rotation**	*Growing a different crop on a given land area every growing/planting cycle and season.*
29.	**Erosion control**	*the creation of some physical barrier, such as vegetation or rock, to absorb some of the energy of the water, causing erosion*

31.	**Chemical fertilisers**	*Substance applied to soils or directly onto plants to provide nutrients optimal for their growth and development*
32.	**Compost**	*Decayed organic material used as a fertiliser for growing plants*
33.	**Leguminous crops**	*Crops from the legumes family can increase soil nutrients like nitrogen*
34.	**Reforestation**	*The replanting of trees on the land that has previously had trees, but where these were cut down recently*
35.	**Conservation agriculture**	*A farming system that can prevent losses of arable land while regenerating degraded lands*
36.	**By-laws**	*A regulation made by a local or traditional authority*
37.	**Natural regeneration**	*The process by which juvenile plants and coppice that have established naturally replace plants which have died or have been killed*
38.	**Seed testing**	*The process of identifying the health quality of seed and germination rate, especially by soaking in water for 24 hours*
39.	**Sowing in rows**	*A spacing of 75 cm between rows, with 25 cm within a row, is the best for achieving maximum yield, especially for maize*
40.	**Mixed cropping**	*Sowing two or three crops together on the same land, one being the main crop and the others the subsidiaries.*
41.	**Pesticides**	*Any substance used to kill, repel, or control certain forms of plant or animal life that are pests*
42.	**Weedicides**	*Any substance that is sprayed on fields to kill weeds*

Appendix E(ii): Definitions of socioeconomic indicators used in the study

#	Indicator	*Definition*
1.	**Primary crop**	*Crops farmers consider the most important for their households*
2.	**Secondary crop**	*Additional crops cultivated to supplement the primary crop*
3.	**Access to cropland**	*Opportunity to obtain cropland for farming*
4.	**Cropland ownership**	*Opportunity to purchase or inherit cropland for farming*
5.	**Expected yields**	*Estimated crop yields farmers hope to receive at the end of the farming season*
6.	**Actual yields**	*Crop yields farmers receive at the end of the farming season*
7.	**Consumed yields**	*Actual crop yields that are utilised as household food*
8.	**Sold yields**	*Actual crop yields that are taken to the market for sale*
9.	**Yield for other purposes**	*Actual crop yields that are used for festivals, weddings or donated to family members*
10.	**Incomes from yields**	*The amount of money received from crop yield sold*
11.	**Incomes alternative options**	*The amount of money received from engaging in off-farm and non-farm activities*
12.	**Remittances**	*Sum of monies received from family members who have migrated to other communities or cities temporarily or permanently*
13.	**Savings**	*Sum of money or potion of income set aside for future use and not spent immediately or as expenditure*
14.	**Loans**	*Sum of money borrowed that is expected to be paid back with interest*
16.	**Credit**	*Contractual agreement in which farmers receive monies or farm inputs and agree to pay later, usually with interest.*

17.	**Insurance**	*Arrangement by which a company or the state provide compensation for poor harvest due to natural disaster*
18.	**Expenditure**	*Sum of money farmers spends wholly and exclusively on their farming*
19.	**Food availability**	*Availability of sufficient quantities of food in appropriate quality, supplied through domestic production*
20.	**Food access**	*Access by individuals to adequate resources (entitlements) for acquiring appropriate foods for a nutritious diet*
21.	**Food utilisation**	*Safe and nutritious food which meets their dietary needs*
22.	**Farm tools**	*Instruments used on farms to aid work, reduce labour, and improve effectiveness.*
23.	**Extension**	*The process of developing agricultural knowledge and skills amongst farmers to productivity and realising other desirable changes*
24.	**Information**	*Various sets of messages that are relevant to agricultural production activities of farmers, such as crop production and protection and natural resource production and conservation*
25.	**Machinery**	*Relates to the mechanical structures and devices used in farming or other agriculture*
26.	**Storage**	*Involves holding and preserving goods from the time they are produced until they are needed for consumption or sales*
27.	**Market**	*Services involved in moving crop yields from the farm to the consumers*
28.	**Alternative livelihood option**	*Livelihood activities that supplement farmers' basic income from farming*
29.	**Migration**	*Movement of people from farming communities to other communities or cities for permanent or temporal labour work*
30.	**Conflicts over resources**	*Serious disagreement or argument over shared farm resources, including land or water*
31.	**Gender inclusion**	*Acknowledging that everyone deserves to be treated with respect regardless of gender identity and ensuring that systems and processes treat all genders equally*
32.	**Labour**	*Involvement of any person in connection with cultivating any agricultural commodity*
33.	**Village Savings and Loans Association (VSLA)**	*Self-managed and self-capitalised savings groups that use members' savings to lend to each other*

Appendix F: Secondary data from the Department of Agriculture in RVB and BVB.

Appendix F(i): The number of on-farm training activities and beneficiaries in 2020 between RVB and BVB

Category	*Type*	*RVB*			*BVB*		
		Training	*Farmers*	*Total No. of farmers*	*Training*	*Farmers*	*Total No. of farmers*
Water management	*Improved seeds (Drought resistant maize varieties)*	*6*	*506*		*4*	*100*	
	water harvesting	*0*	*0*		*0*	*0*	
	Irrigation (Dugouts, wells for dry season farming)	*3*	*413*		*18*	*1482*	
	Mulching	*6*	*120*		*3*	*45*	
	Sub-Total	***15***	***1039***	***65,936***	***25***	***1627***	***59,222***
Soil management	*Chemical fertilisers*	*6*	*1337*		*3*	*50*	
	Leguminous crops	*6*	*142*		*3*	*75*	
	Organic matter	*6*	*1500*		*3*	*50*	
	Soil erosion	*6*	*1007*		*5*	*93*	
	Zero Tillage	*6*	*927*		*4*	*245*	
	Crop rotation	*6*	*2134*		*34*	*3322*	
	Sub-Total	***36***	***7047***	***65,936***	***52***	***3835***	***59,222***
Crop management	*Pest/disease control (Fall armyworm and Striga control)*	*3*	*1333*		*5*	*566*	
	Sowing in rows	*6*	*1187*		*0*	*0*	
	Mixed cropping	*6*	*120*		*0*	*0*	
	seed testing	*0*	*0*		*0*	*0*	
	Sub-Total	***15***	***2640***	***65,936***	***5***	***566***	***59,222***
Ecosystem management	*Bushfire control*	*12*	*1277*		*35*	*4310*	
	Afforestation	*3*	*1248*		*12*	*1556*	
	Sub-Total	***15***	***2525***		***47***	***5866***	***59,222***
Total		***81***	***13251***		***129***	***11894***	

Source: (Bongo-DOA, 2020; Lawra-DOA, 2020)

Appendix F(ii): Comparing the distribution of agrochemicals by gender in RVB and BVB

Type of Chemical	*Beneficiaries in BV*			*Beneficiaries in RV*		
	Quantity	*No. of Male*	*No. of Females*	*Quantity*	*No. of Males*	*No. of Females*
Eradicoat	*42 Litres*	*39*	*5*	*130 Liters*	*154*	*101*
Adepa	*312 Litres*	*549*	*132*	*3 Liters*	*11*	*5*
Warrior super	*132 Litres*	*128*	*59*	*100 Liters*	*207*	*171*
Agoo	*60 Litres*	*137*	*63*	*60 Liters*	*72*	*67*
Bypel	*50 sachets*	*13*	*12*	*250 sachets*	*76*	*89*
Nova BT	*130 sachets*	*47*	*44*	*100 sachets*	*122*	*67*
Total		***913***	***315***		***642***	***500***

Source: (Bongo-DOA, 2020; Lawra-DOA, 2020)

Appendix F(iii): The number of visitations to farmers made by AEAs in RVB and BVB.

Basin	*2019*		*2020*	
	No. of Visits	*No. of farmers visited*	*No. of Visits*	*No. of farmers visited*
RVB	*72,769*	*92,941*	*46,124*	*107,314*
BVB	-	*20,742*	-	*12,669*

Source: (Bongo-DOA, 2020; Lawra-DOA, 2020)

Appendix F(iv): Quantity of input distribution through the PFJ in the Red Volta and BVB

Input	*Type*	*Unit*	*Opening stock*		*Distributed*	
			Red Volta	*Black Volta*	*Red Volta*	*Black Volta*
Fertilisers	*NPK*	*kg*	*35,860*	*12,822*	*30,660*	*12,822*
Improved seeds	*Maize*	*kg*	*29,700*	-	*29,700*	-
Chemical	*Adepa*	*litres*	*130*	*100*	*60*	*30*

Source: (Lawra-DoA, 2020; Bongo-DoA, 2020)

Appendix F(v): *Institutional stakeholders (workshop participants) and their role within the agriculture system in RVB and BVB*

	Institution	***Role***	***Stakeholder type***	***No. of participants***					
				RVB			***BVB***		
				M	***F***	***T***	***M***	***F***	***T***
1	*FBO*	*Mostly self-organised farmer groups that support each other with information, technology, financing, and inputs*	*Group leaders and experienced farmers*	*3*	*2*	*5*	*3*	*2*	*5*
2	*DOA Extension service*	*Mandated province field support and advisory to farmers within all communities*	*AEAs, AEA assistants and Department head*	*3*	*2*	*5*	*5*	*0*	*5*
3	*Community leadership*	*They are the most respected voices in farming communities' conflicts and allocating agricultural resources such as farmland and inputs.*	*Chiefs, Queen mothers, opinion leaders and assembly members*	*5*	*0*	*5*	*3*	*2*	*5*
4	*Private input suppliers*	*They supply farm inputs (fertilisers, improved seeds, agrochemicals, and farm tools), financial (loans/credit) and hiring (machinery) services to farmers.*	*Input retailers*	*4*	*1*	*5*	*4*	*1*	*5*
5	*NGOs*	*support farmers with extension and livelihood implementation activities that sustainably boost foods security, environmental management, and reduce poverty*	*Field officers and technical officers, NGO heads*	*4*	*1*	*5*	*3*	*2*	*5*
Total				***18***	***6***	***25***	***19***	***7***	***25***

Appendix G: Supplementary results from chapter 5

***Appendix G(i):** Stepwise linear regression showing biophysical risk perceptions that predict actual yield/ha in RVB.*

Model Summary[a]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.482[b]	.232	.228	.22434
2	.530[c]	.281	.273	.21774
3	.561[d]	.315	.303	.21312
4	.591[e]	.349	.334	.20830

a. Name of district = RVB

b. Predictors: (Constant), IT

c. Predictors: (Constant), IT, DSN

d. Predictors: (Constant), IT, DSN, SF

e. Predictors: (Constant), IT, DSN, SF, ER

Coefficients[a,b]

Model		Unstandardized Coefficients		Standardized Coefficients		
		B	Std. Error	Beta	t	Sig.
1	(Constant)	.812	.033		24.296	<.001
	IT	-.283	.039	-.482	-7.337	<.001
2	(Constant)	.895	.040		22.222	<.001
	IT	-.227	.041	-.387	-5.565	<.001
	DSN	-.154	.045	-.240	-3.456	<.001
3	(Constant)	.903	.040		22.853	<.001
	IT	-.197	.041	-.335	-4.766	<.001
	DSN	-.136	.044	-.211	-3.071	.002
	SF	-.101	.034	-.197	-2.961	.003
4	(Constant)	1.042	.060		17.381	<.001
	IT	-.170	.041	-.289	-4.118	<.001
	DSN	-.116	.044	-.180	-2.658	.009
	SF	-.111	.033	-.216	-3.310	.001
	ER	-.185	.061	-.195	-3.040	.003

a. Name of district = RVB

b. Dependent Variable: Actual_sum

Appendix G(ii): *Stepwise linear regression showing adopted on-farm strategies that predict expected yield/ha in RVB.*

Model Summary[a]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.390[b]	.152	.147	.47467
2	.468[c]	.219	.211	.45663
3	.494[d]	.244	.232	.45042

a. Name of district = RVB

b. Predictors: (Constant), adopted crop rotation with legumes

c. Predictors: (Constant), adopted crop rotation with legumes, adopted water harvesting

d. Predictors: (Constant), adopted crop rotation with legumes, adopted water harvesting, adopted mulching on farm

Coefficients[a,b]

Model		Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.
1	(Constant)	1.424	.063		22.651	<.001
	adopted crop rotation with legumes	-.441	.075	-.390	-5.922	<.001
2	(Constant)	1.341	.064		21.011	<.001
	adopted crop rotation with legumes	-.440	.072	-.388	-6.139	<.001
	adopted water harvesting	.297	.072	.259	4.098	<.001
3	(Constant)	1.351	.063		21.422	<.001
	adopted crop rotation with legumes	-.400	.072	-.353	-5.514	<.001
	adopted water harvesting	.332	.073	.290	4.560	<.001
	adopted mulching on farm	-.195	.077	-.165	-2.532	.012

a. Name of district = RVB

b. Dependent Variable: Expected_sum

Appendix G(iii): *Stepwise linear regression showing adopted on-farm strategies that predict expected yield/ha in BVB.*

Model Summary[a]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.148[b]	.022	.017	.33044
2	.217[c]	.047	.037	.32700

a. Name of district = BVB

b. Predictors: (Constant), adopted growing improved seeds

c. Predictors: (Constant), adopted growing improved seeds, adopted seed testing before sowing

Coefficients[a,b]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	.849	.035		24.228	<.001
	adopted growing improved seeds	.099	.048	.148	2.072	.040
2	(Constant)	.853	.035		24.573	<.001
	adopted growing improved seeds	.163	.055	.244	2.952	.004
	adopted seed testing before sowing	-.137	.061	-.186	-2.246	.026

a. Name of district = BVB

b. Dependent Variable: Expected_sum

Appendix G(iv): *Stepwise linear regression showing adopted on-farm strategies that predict actual yield/ha in RVB.*

Model Summary[a]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.485[b]	.236	.232	.22213
2	.519[c]	.270	.262	.21770
3	.542[d]	.294	.283	.21461

a. Name of district = RVB

b. Predictors: (Constant), adopted crop rotation with legumes

c. Predictors: (Constant), adopted crop rotation with legumes, adopted pest/disease control (pesticides,weedicides)

d. Predictors: (Constant), adopted crop rotation with legumes, adopted pest/disease control (pesticides,weedicides), adopted sowing in rows

Coefficients[a,b]

Model		Unstandardized Coefficients B	Std. Error	Standardized Coefficients Beta	t	Sig.
1	(Constant)	.800	.031		25.958	<.001
	adopted crop rotation with legumes	-.274	.036	-.485	-7.572	<.001
2	(Constant)	.673	.053		12.772	<.001
	adopted crop rotation with legumes	-.258	.036	-.457	-7.191	<.001
	adopted pest/disease control (pesticides, weedicides)	.135	.046	.187	2.941	.004
3	(Constant)	.589	.062		9.580	<.001
	adopted crop rotation with legumes	-.282	.037	-.500	-7.701	<.001
	adopted pest/disease control (pesticides, weedicides)	.148	.045	.205	3.248	.001
	adopted sowing in rows	.109	.043	.164	2.524	.012

a. Name of district = RVB

b. Dependent Variable: Actual_sum

Appendix G(v): *Stepwise linear regression showing adopted on-farm strategies that predict actual yield/ha in BVB.*

Model Summary[a]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.182[b]	.033	.028	.23389
2	.249[c]	.062	.052	.23100
3	.286[d]	.082	.067	.22914

a. Name of district = BVB

b. Predictors: (Constant), adopted mixed cropping

c. Predictors: (Constant), adopted mixed cropping, adopted growing improved seeds

d. Predictors: (Constant), adopted mixed cropping, adopted growing improved seeds, adopted erosion control (terracing, contour bands)

Model		Unstandardized Coefficients B	Std. Error	Standardized Coefficients Beta	t	Sig.
1	(Constant)	.668	.046		14.554	<.001
	adopted mixed cropping	-.126	.049	-.182	-2.554	.011
2	(Constant)	.630	.048		13.173	<.001
	adopted mixed cropping	-.133	.049	-.192	-2.729	.007
	adopted growing improved seeds	.081	.033	.170	2.413	.017
3	(Constant)	.655	.049		13.368	<.001
	adopted mixed cropping	-.134	.048	-.193	-2.764	.006
	adopted growing improved seeds	.104	.035	.220	2.970	.003
	adopted erosion control (terracing, contour bands)	-.071	.035	-.150	-2.024	.044

Coefficients[a,b]

a. Name of district = BVB

b. Dependent Variable: Actual_sum

Appendix G(vi): *Ordinal logistic regression showing the number of adopted on-farm strategies that predict cropland size, access to inputs and services, expenditure, expected yields/ha and actual yield/ha in RVB.*

Pseudo R-Square[a]

Cox and Snell	.305
Nagelkerke	.311
McFadden	.093

Link function: Logit.

a. Name of district = RVB

Parameter Estimates[a]

		Estimate	Std. Error	Wald	df	Sig.	95% Confidence Interval Lower Bound	Upper Bound
Threshold	[sum_strategies = 4.00]	-1.535	1.350	1.292	1	.256	-4.181	1.112
	[sum_strategies = 5.00]	-.817	1.179	.481	1	.488	-3.128	1.493
	[sum_strategies = 6.00]	1.705	1.116	2.332	1	.127	-.483	3.892
	[sum_strategies = 7.00]	3.454	1.166	8.783	1	.003	1.170	5.739
	[sum_strategies = 8.00]	4.487	1.187	14.291	1	<.001	2.160	6.813
	[sum_strategies = 9.00]	5.750	1.200	22.947	1	<.001	3.397	8.103
	[sum_strategies = 10.00]	6.764	1.209	31.274	1	<.001	4.393	9.134
	[sum_strategies = 11.00]	7.773	1.224	40.304	1	<.001	5.373	10.172
	[sum_strategies = 12.00]	9.757	1.337	53.263	1	<.001	7.137	12.378
Location	total_land_area_ha	-.122	.128	.906	1	.011	-.373	.129
	Inputs_access	2.558	.993	6.629	1	.010	.611	4.505
	Services_access	3.560	.544	42.775	1	<.001	2.493	4.627
	expenditure_GH_HA	.002	.001	6.435	1	.011	.000	.003
	Expected_sum	-.301	.382	.619	1	.431	-1.049	.448
	Actual_sum	-.968	.787	1.513	1	.050	-2.511	.574

Link function: Logit.

a. Name of district = RVB

Appendix G(vii): *Ordinal logistic regression showing the number of adopted on-farm strategies that predict cropland size, access to inputs and services, expenditure, expected yields/ha and actual yield/ha in BVB.*

Pseudo R-Square[a]

Cox and Snell	.170
Nagelkerke	.171
McFadden	.040

Link function: Logit.

a. Name of district = BVB

Parameter Estimates[a]

		Estimate	Std. Error	Wald	df	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Threshold	[sum_strategies = 2.00]	-2.770	1.132	5.985	1	.014	-4.989	-.551
	[sum_strategies = 3.00]	-.951	.685	1.930	1	.165	-2.293	.391
	[sum_strategies = 4.00]	.018	.624	.001	1	.977	-1.206	1.241
	[sum_strategies = 5.00]	1.167	.621	3.531	1	.060	-.050	2.385
	[sum_strategies = 6.00]	2.057	.635	10.502	1	.001	.813	3.302
	[sum_strategies = 7.00]	2.667	.645	17.093	1	<.001	1.403	3.932
	[sum_strategies = 8.00]	3.182	.654	23.696	1	<.001	1.901	4.463
	[sum_strategies = 9.00]	3.611	.661	29.891	1	<.001	2.317	4.906
	[sum_strategies = 10.00]	4.074	.668	37.140	1	<.001	2.763	5.384
	[sum_strategies = 11.00]	4.783	.683	49.037	1	<.001	3.444	6.122
	[sum_strategies = 12.00]	5.782	.718	64.791	1	<.001	4.374	7.190
Location	total_land_area_ha	.231	.105	4.852	1	.028	.025	.437
	Inputs_access	.708	.442	2.562	1	.049	-.159	1.575
	Services_access	1.636	.532	9.450	1	.002	.593	2.678
	expenditure_GH_HA	.001	.001	6.464	1	.011	.000	.003
	Expected_sum	.471	.596	.626	1	.429	-.696	1.639
	Actual_sum	-1.235	.838	2.172	1	.050	-2.878	.407

Link function: Logit.

a. Name of district = BVB

Appendix G(viii): *Pearson's t-test results show the differences (p-values) between respondents' characteristics (community, gender, age, education, extension access and information access) for biophysical risk perceptions (approximate variable) and the number of adopted on-farm strategies in RVB and BVB.*

Determinants	**Basin**	**Biophysical risk perception (P-Values)**				**On-farm management strategies (P-Value)**		
		Water	***Soil***	***Ecosystem***	***Crop***	***Water***	***Soil***	***Crop***
Community	*RVB*	<0.001*	0.634	0.588	0.106	<0.001*	0.258	0.569
	BVB	0.528	0.71	0.004*	0.101	0.04*	0.456	0.278
Gender	*RVB*	0.049*	0.4*	0.968	0.668	0.854	0.418	0.345
	BVB	0.048*	0.398	0.509	0.006*	<0.001*	0.044*	0.018*
Age	*RVB*	<0.001*	<0.001*	<0.001*	0.019*	0.08*	0.753	<0.001*
	BVB	0.448	0.015*	0.002*	0.766	0.018*	0.49	0.044*
Education	*RVB*	0.022*	0.052*	0.208	0.024*	0.553	0.008*	0.003*
	BVB	0.583	0.143	0.539	0.106	0.05*	0.514	0.294
Extension	*RVB*	0.58	0.273	0.609	0.553	0.05*	0.005*	<.001*
	BVB	0.368	0.028*	<0.001*	<0.001*	<.001*	<0.001*	<0.001*
Information	*RVB*	0.004*	<0.001*	0.102	0.512	0.392	<0.001*	0.046*
	BVB	0.572	0.044*	<0.001*	0.013*	<.001*	<0.001*	<.001*

****Significance level (p ≤ 0.05)***

Appendix H: Supplementary results from chapter 6

Appendix H (i): Box and whisker plot explained

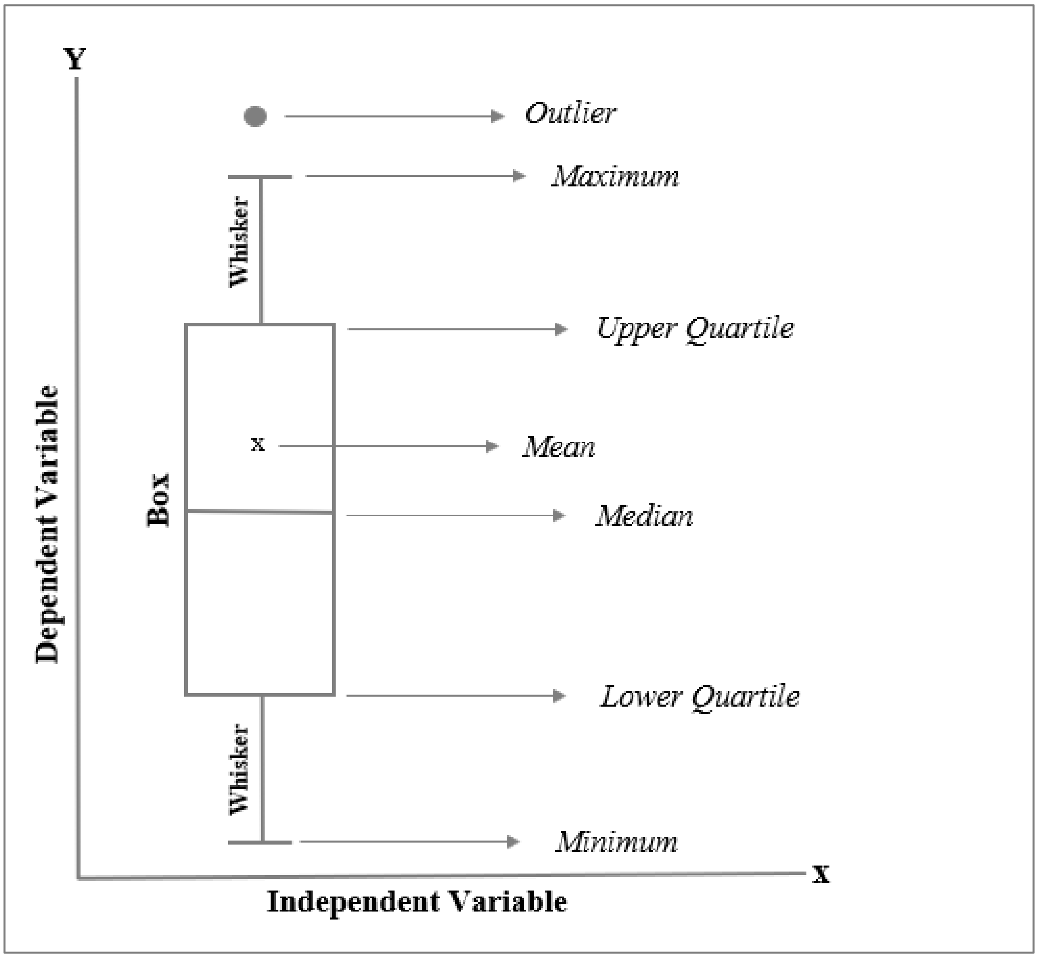


Figure 1: *Showing box and whisker plot and its components.*

In a box and whisker plot:

- The top and bottom edges of the box are the upper and lower quartiles. The box covers the interquartile interval, where 50% of the data is found.
- The horizontal line that divides the box in two is the median.
- The mean is indicated with a cross on the box plot.
- The whiskers are the two lines outside the box, running from the minimum to the lower quartile (the start of the box) and from the upper quartile (the end of the box) to the maximum.
- The X-axis represent the independent variable, and the Y-axis represents the dependent variables.

Appendix H(i): Kruskal Willis H and Mann-Whitney U test results showing the determinants of primary (Maize) and secondary crop (Cereals/legumes) yields in RVB and BVB.

			Primary crop (p-values)		**Secondary Crop (p-values)**	
Tests	**Determinants**	**Basin**	**Expected**	**Actual**	**Expected**	**Actual**
Kruskal Willis H test	Communities	*RVB*	0.28	0.86	0.63	0.02*
		BVB	0.69	0.004*	0.24	0.03*
	Gender	*RVB*	.813	.043*	.428	.636
		BVB	.516	.889	.279	.439
	Education	*RVB*	0.139	0.008*	0.717	0.307
		BVB	0.291	0.064	0.024*	0.037*
Mann-Whitney U test	Extension	*RVB*	0.805	<.001*	0.363	0.161
		BVB	0.42	0.069	0.394	0.05*
	FBO	*RVB*	0.57	0.002*	0.75	0.65
		BVB	0.48	0.22	0.1	0.04*
	credit	*RVB*	0.024*	0.05*	0.762	0.399
		BVB	0.563	0.929	0.006*	0.008*

***Significance level (p ≤ 0.05)**

Appendix H(ii): *Stepwise linear regression showing the inputs and services that could predict actual primary yield/ha in RVB.*

Coefficients[a,b]

Model		Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.
1	(Constant)	.832	.034		24.681	<.001
	access info	-.249	.042	-.394	-5.872	<.001
2	(Constant)	.720	.050		14.520	<.001
	access info	-.261	.042	-.413	-6.264	<.001
	access fertilizer	.150	.050	.199	3.019	.003
3	(Constant)	.712	.049		14.462	<.001
	access info	-.242	.042	-.383	-5.734	<.001
	access fertilizer	.183	.052	.243	3.546	<.001
	tractor access	-.098	.046	-.149	-2.128	.035

a. Name of district = RVB

b. Dependent Variable: Actual_maize_MT_HA

Appendix H(iii): *Stepwise linear regression showing the inputs and services that could predict actual secondary yield/ha in RVB.*

Coefficients[a,b]

Model		Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.
1	(Constant)	.435	.032		13.395	<.001
	access storage	.155	.044	.255	3.519	<.001

a. Name of district = RVB

b. Dependent Variable: Actual_crop2_MT_HA

Appendix H(iv): *Stepwise linear regression showing the inputs and services that could predict actual secondary yield/ha in BVB.*

Coefficients[a,b]

Model		Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.
1	(Constant)	.601	.022		26.791	<.001
	access credit	.275	.086	.225	3.187	.002
2	(Constant)	.551	.029		18.900	<.001
	access credit	.247	.086	.202	2.881	.004
	access seed	.112	.043	.182	2.594	.010

a. Name of district = BVB

b. Dependent Variable: Actual_crop2_MT_HA

Appendix H(v): *Mann-Whitney U test showing the determinants of farm expenditure, yield income and profits/losses in RVB and BVB.*

		p-values		
Determinants	***Basin***	**Expenditure**	**Incomes**	**Profit/losses**
	RVB	0.575	0.328	0.459
Gender	*BVB*	0.003*	0.095	0.81
	RVB	0.002*	0.001*	0.743
Age	*BVB*	0.005*	0.037*	0.448
	RVB	0.157	0.018*	0.846
Education	*BVB*	0.005*	0.026*	0.831
	RVB	0.253	0.699	0.639
Extension	*BVB*	0.015	0.05*	0.851
	RVB	0.002*	0.05*	0.33
FBO	*BVB*	<.001*	<.001*	0.178

Significance level ($p \leq 0.05$)

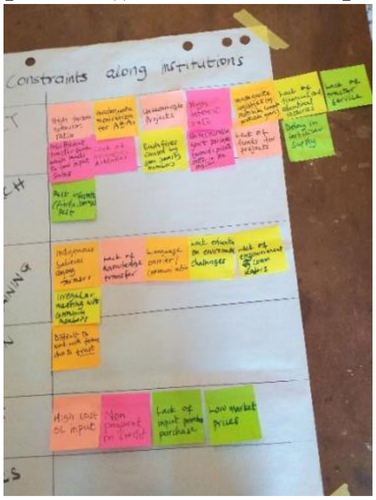
Appendix H(v): *Kruskal Willis H and Mann-Whitney U test results indicating the p-values for the determinants of Off-farm income (alternative livelihood incomes and remittances) in RVB and BVB.*

			p-values		
Test	**Determinants**	**Basin**	**Alternative livelihood**	***Remittances***	**Off-farm incomes**
Kruskal Willis H test	Communities	*RVB*	0.003*	0.002*	<.001*
		BVB	0.195	0.852	0.348
Mann-Whitney U t-test	Gender	*RVB*	0.224	0.687	0.326
		BVB	<.001*	0.125	<.001*
	Education	*RVB*	0.004*	0.008*	<.001*
		BVB	0.05*	0.099	0.037*

Significance level ($p \le 0.05$)

Appendix I: Posters from stakeholder engagement activities in RVB and BVB

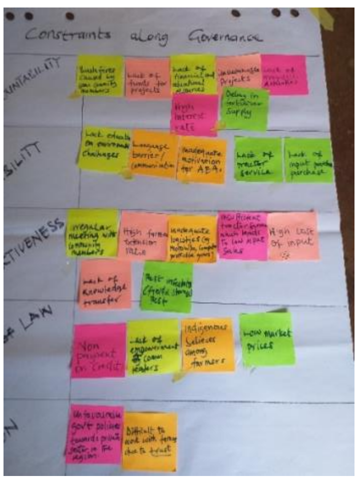
Appendix I(i): Stakeholder outputs from the workshop in RVB



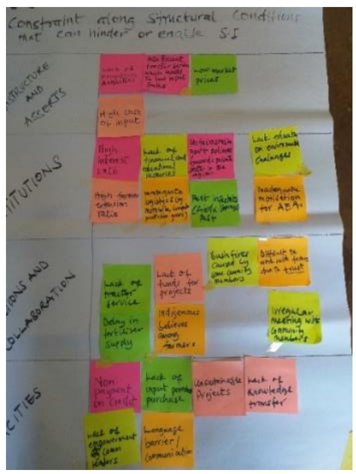
Constraints along institutions

Constraints along administrative

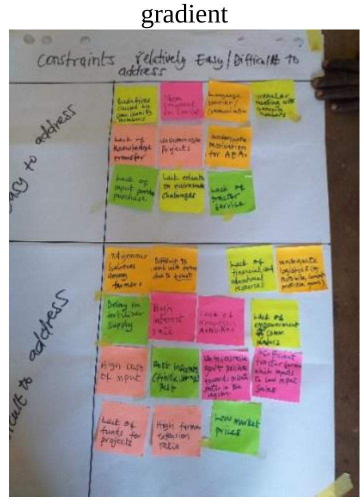
Constraints along the 4-step gradient



Constraints along governance structure

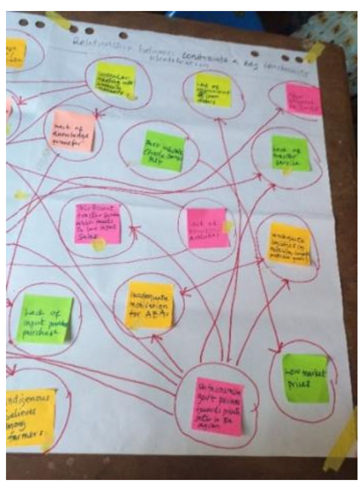


Constraints along the structural condition



Constraints easy/difficult to address

Constraints relationship 1

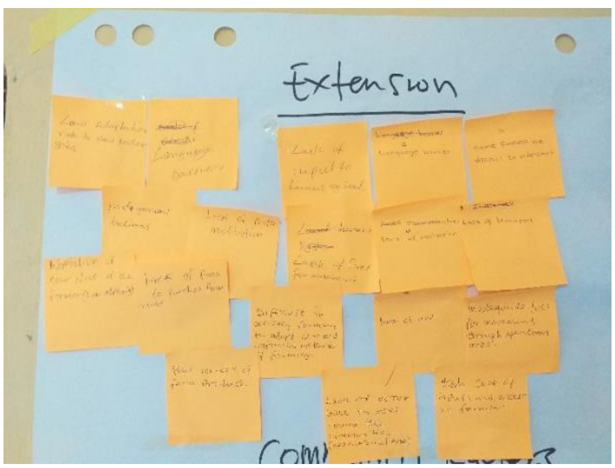


Constraints relationship 2

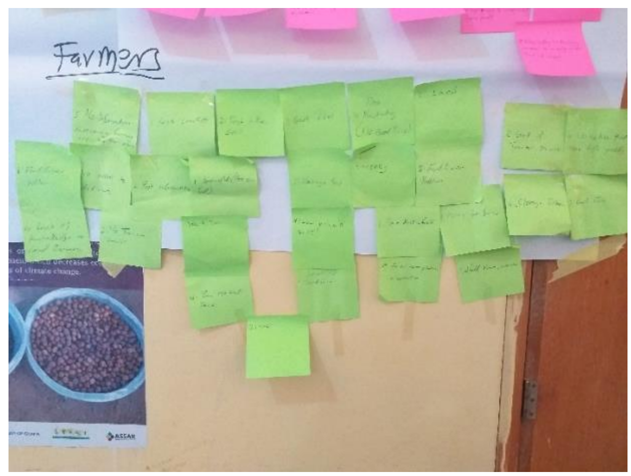
Constraints addressed within groups or collaboratively

Strategies to address top-5 constraints

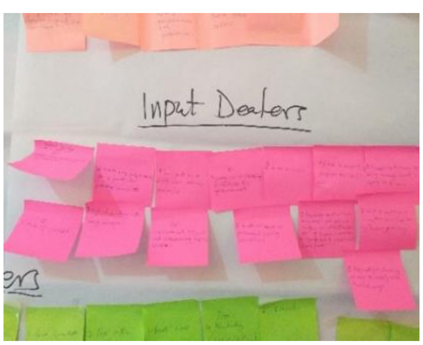
Timelines to address top-5 constraints



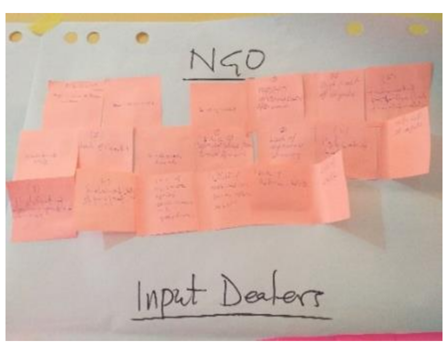
Extension constraints



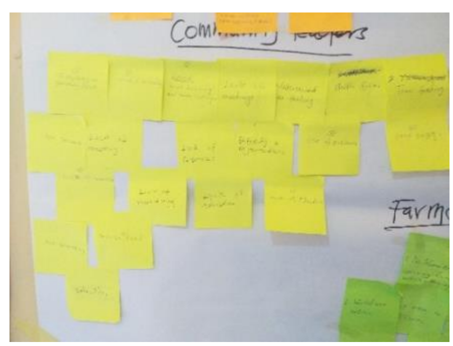
Farmers constraints



Input dealers/suppliers constraints



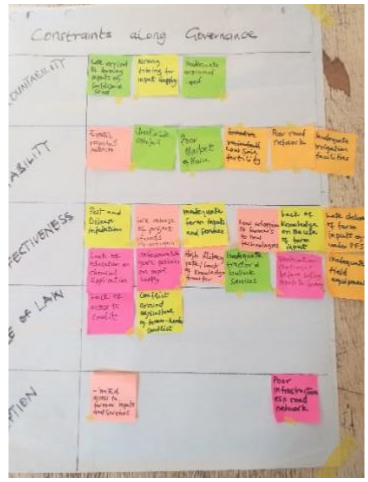
NGOs constraints


Community leaders constraints

Appendix I(ii): Stakeholder outputs from the workshop in RVB


Constraints along institutions


Constraints along administrative

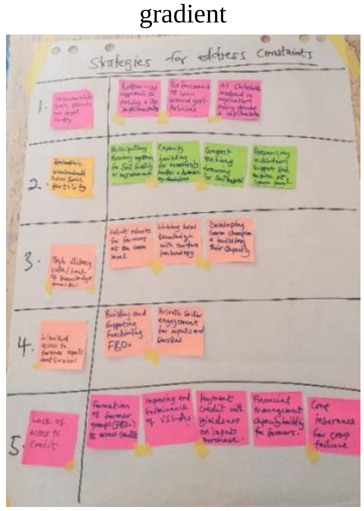

Constraints along governance structure


Constraints along the structural condition


Constraints along the 4-step gradient


Constraints easy/difficult to address


Constraints addressed within groups or collaboratively


Strategies to address top-5 constraints


Timelines to address top-5 constraints

Constraints relationship

Stakeholder Constraints

Appendix J: Media stories describing input smuggling in study sites

UPPER WEST REGIONAL CO-ORDINATING COUNCIL

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Two Trucks Loaded With 50kg of Fertilizer Believed To Be Smuggled Fertilizer In The Upper West Region was Impounded on By The National Security Laision Officer

Barely a week ago when the Upper West Regional Minister in his bid to fighting fertilizer smuggling in the region meant for the Planting for Food and Jobs Program, urged the people of Upper West to all be vigilant and report any suspected fertilizer smuggling to the police for necessary actions; two trucks loaded with 50kg of fertilizer believed to be smuggled fertilizer in the Upper West Region was impounded on by the National Security Laision Officer on 26th April 2019 in Wa.

The tracks which contained two thousand bags of unapproved fertilizers were intercepted by the National Security in the Upper West Region.

Two articulated trucks carrying 50 kilogrammes of fertilizers from a vendor John Dor Ventures at Nkoranza to B.B. Slow, a distributor at Gwollu in the Sissala West District were both impounded.

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Ghana loses GHS120m to fertilizer smuggling – PFJ Secretariat

May 7, 2020

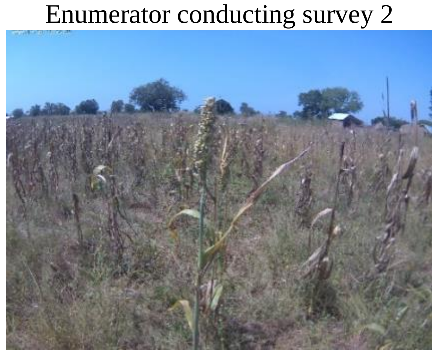
Appendix K: Pictures from the field in RVB and BVB

Enumerator conducting survey 1

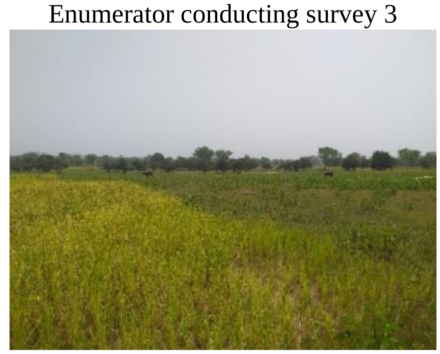
Enumerator conducting survey 2

Enumerator conducting survey 3

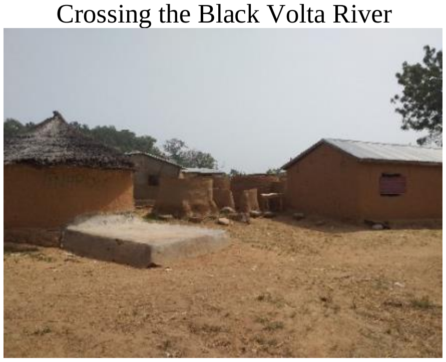
Crossing the Black Volta River



Sorghum field ready for harvesting RVB



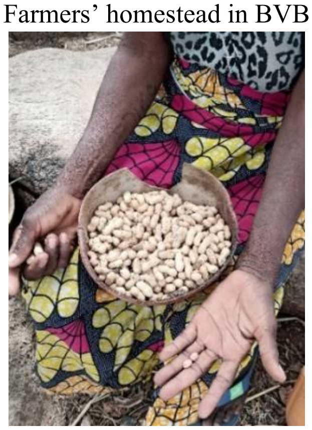
Rice fields in RVB



Farmers' homestead in BVB

DOA extension project in RVB

Agrochemicals in input retailers shop in RVB



Female farmer with groundnut harvest in BVB

Homestead silos for maize storage in RVB

Farmer with cow dung for compost and organic manure in RVB

Stakeholder engagement in BVB

Focus group discussions in RVB

Stakeholder engagement in RVB

Researchers engaging with farmers in RVB

Harvested maize field in RVB

Compound cropland area homestead in BVB

Farmers selling their fields in the market in BVB

Local beer sales at the market as off-farm income generating activity in RVB

Women weaving local textile in RVB

Irrigated fields in RVB

Water shortages in small dam in RVB

Road network in BVB