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Contents

Introduction

Sub-Saharan Africa faces significant challenges stemming from rapid population growth and vulnerability to climate change, which jeopardize food security and hinder poverty alleviation efforts. Agriculture is the cornerstone for addressing these issues, with smallholders comprising the bulk of African agricultural producers who play a critical role in bolstering food production and driving economic development. However, smallholder agriculture remains hindered by several obstacles, including restricted access to quality inputs, inadequate infrastructure, and insufficient extension services. These challenges are exacerbated by climatic risks and market fluctuations, such as unpredictable rainfall patterns and economic downturns, which severely impact crop yields and income stability. Furthermore, widespread land degradation and declining soil fertility threaten the long-term viability of agricultural productivity.

To address these issues, targeted policies and innovative technological interventions have been implemented across sub-Saharan Africa to promote sustainable intensification and climate-resilient smallholder farming systems. However, empirical research reveals that the impact of these measures on improving smallholder income or welfare is often insignificant. Regardless of how sustainable or innovative a technology may appear, its widespread adoption by smallholders is neither likely nor advisable if it does not substantially improve their livelihoods. One factor underlying this limited impact is the tradeoff in allocating scarce resources among diverse livelihood activities. Agricultural innovations often demand higher inputs and labor, creating competing production priorities. Thus, optimizing agricultural systems to reduce tradeoffs and enhance overall benefits is crucial for encouraging smallholders to adopt and disseminate beneficial technologies. Unfortunately, such initiatives have been scarce, leaving a significant gap in support for informed decision-making.

This report presents research findings on the development and application of the African Smallholder Farm Management Model (ASFAM), aimed at addressing these critical challenges comprehensively. ASFAM has been applied in various development projects of the Japan International Research Center for Agricultural Sciences (JIRCAS) across upland cropping, rice cultivation, vegetable farming, and livestock production. These applications have identified optimal production combinations and technologies to maximize their impact on household food security and income. This report systematically organizes and showcases these outcomes.

The report consists of five chapters. Chapter 1 introduces the conceptualization of ASFAM as an integrated, multi-objective farm management model designed to support smallholders' decision-making by explicitly incorporating their diverse production systems and livelihood strategies. It also highlights case studies on optimizing and diagnosing cropping systems across agroecological zones using ASFAM. Chapters 2 through 4 detail the findings from ASFAM research conducted in JIRCAS-led projects across multiple African countries. These chapters address upland cropping systems, lowland cropping systems, and livestock systems, respectively, identifying critical barriers to the adoption of recommended technologies by smallholders and presenting model-based solutions to optimize technology uptake.

Chapter 5 introduces practical tools that facilitate ASFAM's application, such as farm-based recordkeeping systems and user-friendly model execution software, along with insights and lessons learned from their deployment across various African nations. It also highlights the outcomes of using ASFAM to support smallholder decision-making, including farmers' evaluation of the decision-support tools and the tangible benefits of their application.

Chapter 1 Development of farm management models in African contexts

1-1 Characteristics of African smallholder livelihoods and their implications for the development of farm management models

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Abstract

Agricultural development in sub-Saharan Africa has increasingly emphasized evidence-based, well-targeted policies and technological innovations aimed at the sustainable intensification of smallholder production systems. However, efforts to address the tradeoffs inherent in allocating scarce resources among competing production demands, including the application of farm management models, have been limited. This paper underscores the distinctive characteristics of African smallholder livelihoods that should be integrated into farm management models, drawing on findings from field surveys conducted across smallholder farming communities in diverse agroecological contexts. The results indicate that many smallholders adopt farming systems to mitigate production and market risks by diversifying crop types and cropping patterns while simultaneously fulfilling household needs for food security and income. Additionally, they engage in livelihood strategies that enhance risk management and ensure the sustainable provision of food and income by securing diverse non-agricultural livelihoods. Therefore, it is crucial to advance whole-farm modeling that incorporates these livelihood strategies comprehensively to support informed decision-making. Farm management models that optimize resource allocation across diverse cropping systems and integrate these systems with diversified non-farm activities will serve as valuable tools for addressing smallholders' livelihood goals and needs.

1. Introduction

Sub-Saharan Africa (SSA) is facing severe challenges due to rapid population growth and vulnerability to climate change, both of which threaten food security and poverty alleviation. The region's population is projected to double from 2020 to 2050, increasing pressure on already limited resources and infrastructure (United Nations, 2019). This rapid expansion has exacerbated food insecurity, with a substantial proportion of the population experiencing hunger and malnutrition (FAO, 2021). Climate change further complicates this situation by intensifying extreme weather events, such as droughts and floods, disproportionately affecting the most vulnerable populations (IPCC, 2018). Moreover, with around 40% of the population living on less than $1.90 per day, SSA remains the region with the highest concentration of extreme poverty (World Bank, 2020).

Agriculture plays a pivotal role in mitigating food insecurity and poverty in SSA. It contributes approximately 17% to the region's GDP and employs 52% of the labor force (World Bank, 2024). Smallholders, who constitute the majority of African agricultural producers, are essential to increasing food production and fostering economic growth. However, the potential of smallholder agriculture is constrained by numerous challenges. Consistently low productivity is a significant issue, influenced by limited access to high-quality inputs, inadequate infrastructure, and insufficient extension services. Vulnerability to climatic risks and market fluctuations further exacerbates these challenges, with erratic rainfall patterns and market downturns severely affecting crop yields and income stability. Additionally, land degradation and soil fertility decline are widespread, reducing the long-term sustainability of agricultural production (Lal, 2015).

To address these challenges, targeted policies and innovative technological interventions have been implemented across SSA. Policy measures such as microfinance and input subsidy programs have generated significant enthusiasm for ensuring the sustainable financial inclusion of the rural poor (Jayne et al., 2018; Van Rooyen et al., 2012). Technological advancements, including the promotion of improved crop varieties, efficient use of water resources, integrated soil fertility management, and smart information and communication technologies, have also garnered considerable attention in the context of enhancing sustainable intensification and climate resilience in smallholder agriculture (Burke et al., 2009; Dunjana et al., 2023; Pretty et al., 2011).

Despite the potential of these interventions, their impact on improving smallholder livelihoods is not always significant. Meta-analyses of various agricultural innovations in SSA indicate that their effect on household welfare is modest (Ogundari & Bolarinwa, 2019). A comprehensive review of input subsidy programs, synthesizing nearly 80 related studies from SSA countries, reveals that while subsidized inputs increase grain yields for beneficiary households, the overall production and welfare impact is often less significant than anticipated (Jayne et al., 2018). Although subsidized fertilizer is frequently promoted, its receipt does not significantly enhance total household income (Ricker-Gilbert & Jayne, 2011). Microcredit programs have also produced no measurable increase in household income (Nakano & Magezi, 2020). A systematic review of the evidence on the effectiveness of microfinance in SSA suggests that it has a modest but not uniform positive impact on the livelihoods of the poor (Van Rooyen et al., 2012). Technological innovations face similar challenges. For instance, the adoption of integrated soil fertility management, despite its notable impact on crop yields, exhibits limited or heterogeneous effects on overall household income or welfare (Adolwa et al., 2019; Hörner & Wollni, 2021). The System of Rice Intensification, another well-known resource-efficient production technology, can generate significant yield improvements, yet users do not experience increased household income (Takahashi & Barrett, 2014).

As highlighted by several of the studies referenced above, a critical factor constraining the economic impact of these interventions is the tradeoff in allocating scarce resources across diverse livelihoods (Hörner & Wollni, 2021; Takahashi & Barrett, 2014). Smallholder farmers face tough decisions regarding distributing their limited resources across agricultural and non-agricultural activities. Since agricultural innovations often entail higher input and labor demands for targeted production, achieving household-level benefits requires efficiently reallocating available resources amidst competing production demands. Thus, optimizing agricultural systems to minimize tradeoffs and maximize overall benefits is paramount. A promising approach is to implement comprehensive farm management models customized to the specific circumstances and livelihood strategies of African smallholders and designed to optimize the allocation of their limited resources. However, such initiatives have been scarce, resulting in a significant lack of tools to support informed decision-making.

This paper aims to bridge this gap by exploring the characteristics of African smallholder livelihoods and examining the implications for developing farm management models that could effectively support smallholder decision-making. To this end, it first highlights the commonalities and heterogeneities in their livelihoods based on results from field surveys conducted across various agroecological zones in SSA. It then delves into the agricultural and non-agricultural livelihood diversification and strategies of smallholders using data from a household survey in northern Mozambique. Finally, it concludes with key findings and their implications for developing farm management models.

2. Highlights of African smallholder livelihoods across different agroecological zones

From 2011 to 2017, the author conducted field surveys with smallholders in peri-urban farming communities across five distinct agroecological zones in SSA: humid tropical forest, sub-humid guinea savanna, semi-arid Sudan savanna, sub-humid inland savanna, and semi-arid coastal savanna. A summary of the findings (Table 1) reveals that, although their livelihoods and cropping systems are diverse, a typical primary livelihood strategy across these regions combines crop production and non-agricultural activities. Livestock farming varies by region in terms of the types and scales of livestock, with some areas, such as southern Ghana and northern Mozambique, limited to small poultry farming.

Staple crop production is generally consistent across regions. Maize, in particular, is cultivated as a staple crop in all regions except Burkina Faso, where lower rainfall leads to the predominance of sorghum and millet. Cassava is another staple crop widely cultivated across most regions. Despite regional variations in other crops, a frequent practice of many smallholders is the simultaneous cultivation of staple food crops, dual-purpose crops, and purely cash crops. Staple food crops include maize, cassava, sorghum, and millet; dual-purpose crops include rice, sweet potatoes, cowpeas, common beans, and pigeon peas; and purely cash crops include tree crops and vegetables. Furthermore, smallholders across all regions frequently practice mixed cropping (or intercropping), particularly with upland crops. For example, maize and cowpeas are often mixed or intercropped in northern Ghana, sorghum, millet, and cowpeas in Burkina Faso, and maize and common beans in northern Mozambique.

While the degree of dependence on mixed cropping varies by region, it is often used to hedge against yield reduction caused by droughts, pests, and disease, enhancing food security and income stabilization. Consequently, the extent of reliance on mixed cropping is influenced by regional crop yield risks and the smallholders' tolerance of these risks. Among the surveyed regions, Burkina Faso and Mozambique smallholders, located in semi-arid zones relatively vulnerable to climate variability, exhibit a higher dependence on mixed cropping, often mixing three to five different crops in the same field. Additionally, most farmers implement this mixed cropping practice across multiple fields with varying locations, thereby addressing production risks at both the crop and field levels.

Table 1. Major livelihoods, crops, and cropping types adopted in the surveyed regions

	Southern Ghana	Northern Ghana	Central Burkina Faso	Northern Mozambique	Southern Mozambique
Agroecology	Humid tropical forest	Sub-humid Guinea savanna	Semi-arid Sudan savanna	Sub-humid inland savanna	Semi-arid coastal savanna
Major livelihoods	Crops, poultry, non-farm activities	Crops, ruminants, non-farm activities	Crops, ruminants, non-farm activities	Crops, poultry, non-farm activities	Crops, ruminants, non-farm activities
Major crops grown	Maize, cassava, plantain, cocoyam, cocoa, and oil palm	Maize, cassava, yam, rice, cowpea, groundnut, and pepper	Sorghum, millet, groundnut, cowpea, and bambara bean	Maize, cassava, pigeon pea, common bean, and potato	Maize, cassava, cowpea, sweet potato, and groundnut
Major cropping type	Mono/mixed cropping	Mono/mixed cropping	Mixed cropping	Mixed cropping	Mixed cropping

Source: Author

3. Smallholders' livelihood diversification and strategies: case of northern Mozambique

This section explores the agricultural and non-agricultural livelihood diversification and strategies of smallholder households based on the findings from a questionnaire survey the author conducted in 2016 on 645 randomly selected smallholder households across the eastern, central, and western parts of northern Mozambique.

Table 2 summarizes the status of farmland, labor, machinery, and livestock holdings in the three areas. All three regions engage in upland cultivation as the leading agricultural livelihood, though some lowland use, such as rice cultivation, is observed in the eastern and central regions. Regional differences in farm size are evident, with larger areas in the inland areas (particularly in the west) where the population density is lower. Yet, there is little regional variation in labor force availability. Agricultural operations are predominantly manual, though some farmers in the central part utilize tractors and other agricultural machinery, and approximately half of the farmers in the eastern and western parts employ hired labor. Livestock farming remains small-scale, predominantly involving small livestock such as poultry across all regions, with minimal utilization of draught cattle.

Although the types of cultivated crops vary between the eastern, central, and western parts, a large number of farmers in each area grow a combination of cereals such as maize and sorghum, root crops like cassava and sweet potatoes, and/or legumes including cowpeas, groundnuts, pigeon peas, and common beans (Table 3). Among these, maize is the primary staple of most households in all areas, while the secondary staple varies: cassava in the east, sorghum in the central parts, and common beans in the west (Table 4). Additionally, cowpeas and groundnuts in the east, pigeon peas in the central part, and sweet potatoes and potatoes in the west are not only consumed. Smallholders also sell them as significant income sources. These findings indicate that most smallholders adopt cropping systems that diversify production and market risks while meeting household demand for food security and income. Conversely, no smallholders rely on monoculture farming practices.

Table 2. Farmland, labor, machinery, and livestock holdings in the three areas

	Eastern	Central	Western
Number of household members	5.8	5.5	6.5
Household labor (persons)	3.7	3.6	3.8
Total farmland (ha)	1.69	1.78	2.47
Upland	1.60	1.74	2.47
Lowland	0.09	0.04	0
Agricultural machinery use (%)	0.5	6.9	1.4
Labor employment (%)	51.7	39.1	49.3
Number of cattle	0.2	0	0.1
Number of medium livestock	2.9	0.5	2.4
Number of small livestock	21.5	15.1	11.9

Source: Koide et al., 2018

Table 3. Crop combinations by smallholder households in northern Mozambique (n=645)

Eastern part	Cassava	✓	✓	✓	✓	✓	✓	✓	✓							
	Maize	✓		✓		✓	✓			✓				✓		
	Cowpea	✓	✓	✓				✓		✓	✓		✓	✓		
	Groundnut	✓	✓		✓	✓				✓		✓	✓			
	n	72	55	24	15	13	8	8	4	2	1	1	1	1		
Central part	Maize	✓	✓	✓	✓	✓			✓			✓			✓	
	Pigeon pea	✓	✓	✓	✓		✓			✓			✓			✓
	Sorghum	✓		✓		✓	✓	✓	✓	✓	✓					
	Cassava			✓	✓	✓	✓	✓						✓	✓	✓
	n	66	45	22	21	15	15	11	9	9	6	5	4	2	2	1
Western part	Maize	✓	✓	✓	✓	✓	✓	✓	✓							
	Common bean	✓	✓	✓			✓									
	Sweet potato		✓				✓	✓	✓							
	Potato			✓		✓	✓		✓							
	n	124	26	26	15	5	5	4	2							

Source: Author

Table 4. Household food consumption by crop in northern Mozambique (n=645)

	East		Center		West	
	Consuming households (%)	Avg. amount (kg/year)	Consuming households (%)	Avg. amount (kg/year)	Consuming households (%)	Avg. amount (kg/year)
Cassava	95.6	505	39.5	351	9.2	352
Maize	85.9	396	89.3	413	100	787
Sorghum	2.4	206	77.3	334	2.4	63
Rice	23.4	273	24.0	255	2.4	159
Cowpea	67.8	172	1.7	158	0	NA
Pigeon pea	2.0	182	56.2	155	0	NA
Common bean	0	NA	3.9	98	100	166
Groundnut	21.5	241	0	NA	0	NA
Sweet potato	0.5	720	1.3	147	30.4	304
Potato	0	NA	0.0	NA	27.1	229

Source: Author

Table 5 outlines the predominant cropping systems and their profitability across different areas. In the east, a diverse mixed cropping system, primarily maize, cassava, cowpea, and groundnut, prevails, occupying nearly half of the cultivated land. Similarly, the central part prefers mixed cropping, often combining two main crops—maize, sorghum, and pigeon pea—although monocultures of these crops are also present. In the west, maize and common beans predominate as mixed crops, covering about two-thirds of the cultivated land, while sweet potatoes and potatoes are primarily grown as monocultures on a smaller scale.

The east achieves higher income with less labor through mixed cropping that incorporates legumes. Likewise, in the central part, mixed cropping of low labor-intensive crops, including pigeon peas, tends to result in higher incomes. Given the limited number and scale of farmers utilizing lowland areas, upland crop diversification focuses on mixed cropping of legumes, which appears to be a favorable farm management strategy in both areas, offering risk mitigation and income enhancement. In contrast, in the west, these crops are labor-intensive and grown on a smaller scale, although sweet potatoes and potatoes yield relatively high income. Transitioning from the predominant maize and common bean mixed cropping to sweet potato and potato monocropping could substantially increase farmers' incomes.

However, achieving self-sufficiency in staple food crops is essential for enhancing income. Table 4 shows that 96%, 86%, and 68% of farm households in the eastern part consume cassava, maize, and cowpeas. In the central part, maize, sorghum, and pigeon peas are consumed by 89%, 77%, and 56% of households. In the western region, the primary food crops of all households are maize and common beans. Therefore, farmers must adopt cropping systems that ensure self-sufficiency in these staple food crops.

Table 5. Major cropping systems and their profitability in each area

		Number of plots	Area (ha)	Share (%)	Gross income (Mt/ha)	Seed cost (Mt/ha)	Fertilizer and agroche-mical cost (Mt/ha)	Hired labor cost (Mt/ha)	Other costs (Mt/ha)	Net income (Mt/ha)	Working hours (/ha)
Eastern	Cassava+Maize+Cowpea mixed	19	1.16	6.4	31,062	2,116	0	2,052	122	26,772	1501
	Cassava+Maize+Cowpea+Groundnut mixed	16	1.98	9.1	35,583	2,916	0	6,789	0	25,879	1672
	Cassava+Cowpea mixed	33	0.59	5.6	27,302	2,027	13	4,360	0	20,902	1928
	Cassava+Cowpea+Groundnut mixed	43	0.97	12.0	29,232	3,215	0	5,086	0	20,931	2047
	Cassava+Groundnut mixed	50	0.65	9.4	30,301	6,450	0	5,473	0	18,378	2137
	Rice mono	25	0.37	2.7	30,105	1,304	0	9,141	0	19,660	1846
	Sweet potato mono	13	0.21	0.8	40,216	2,820	0	2,823	0	34,572	1274
Central	Cassava mono	43	0.45	4.8	17,245	798	0	317	0	16,130	1489
	Maize mono	41	0.63	6.4	14,274	522	0	869	120	12,763	1275
	Maize + Pigeon pea mixed	99	1.12	27.3	22,797	925	0	698	95	21,079	1291
	Sorghum mono	77	0.44	8.4	7,918	295	0	288	102	7,233	1328
	Sorghum + Pigeon pea mixed	31	0.41	3.1	22,260	750	0	135	0	21,375	1475
	Rice mono	40	0.19	1.9	26,640	1,326	0	1,397	0	23,917	3115
	Pigeon pea mono	24	0.73	4.3	20,645	647	0	972	158	18,868	955
	Soybean+Pigeon pea mixed	17	1.22	5.1	52,150	1,968	4	4,722	686	44,771	1123
Western	Maize+Common bean mixed	175	1.95	66.9	26,465	2,019	25	1,935	274	22,212	1329
	Maize mono	41	1.47	11.8	27,491	891	300	943	167	25,190	1404
	Common bean mono	9	0.61	1.1	18,564	4,075	110	3,997	330	10,052	1829
	Sweet potato mono	27	0.26	1.4	60,368	3,672	417	3,248	1,178	51,853	2482
	Potato mono	20	0.51	2.0	34,720	4,043	3,876	1,359	67	25,376	2356

Notes:

1) "Share" indicates the area of each crop as a percentage of the total cultivated area in each region.

2) "Mt" is the metical, the currency of Mozambique (the same applies below).

3) Unlike the eastern and central parts, the western area is adjacent to Malawi, where fertilizers and other agrochemicals are procured relatively inexpensively, and some farmers learn how to use them from their relatives living in Malawi. Thus, more farmers in the west use fertilizers and other agrochemicals than those in the eastern and central parts.

Source: Koide et al., 2018

It is crucial to ensure that labor allocation to agriculture does not significantly undermine non-agricultural activities that contribute to household welfare. In all three areas, nearly all farm households engage in firewood collection and water fetching, with some also participating in hunting, fishing in small rivers, gathering non-timber forest products such as fruits and mushrooms, and other non-farm businesses (Table 6). The proportion of households involved in these activities is notably higher in the eastern part than in the west, particularly in collecting non-timber forest products (79%) and non-farm business activities (65%). The central part holds an intermediate position but features a relatively high number of households engaged in hunting (53%), which aligns with the region's small livestock farming practices. Beyond these regional distinctions, certain non-farm activities, such as hunting and gathering, display seasonal patterns. Overall, household labor is distributed relatively evenly throughout the year, preventing the emergence of excessive labor peaks (Figure 1). However, given the substantial labor dedicated year-round to firewood gathering, water fetching, and non-farm business activities—each of which is vital to the life and livelihood of farm households—it is imperative to allocate labor between agricultural and non-agricultural tasks according to the regional and seasonal characteristics of each activity.

The current composition and share of annual income among smallholder households underscore the importance of efficient labor allocation between agricultural and non-agricultural sectors in enhancing overall household income. As shown in Figure 2, crop income constitutes the largest share of household income across all areas. However, the share of other income sources is substantial—approximately 60% in the eastern part and around 40% in the other two areas, rendering them far from negligible. Moreover, these income shares are well-distributed across multiple livelihoods, including livestock, firewood collection, gathering non-timber forest products, and business activities, without significant concentration in any single area. Therefore, an exclusive focus on boosting crop income, leading to an overly large share, could compromise the moderate risk-hedging benefits of diversified livelihoods. This approach is unlikely to be acceptable or beneficial for smallholders. Furthermore, in all areas, other economic activities, apart from livestock farming—which typically involves minimal labor inputs due to the widespread practice of free-ranging small livestock—require substantial labor year-round, as previously mentioned. Hence, merely optimizing labor allocation among production demands to maximize crop income might inadvertently sacrifice non-agricultural income, potentially failing to improve overall household income. As long as smallholders aim for risk management and income improvement across their entire livelihood, crop recommendations that significantly reduce non-agricultural income from its current levels should be avoided. Conversely, significantly increasing the share of non-agricultural livelihoods is neither realistic nor sustainable, given the constraints on the quantity of natural or human resources on which these livelihoods depend.

Table 6. Percentage of smallholder households that engage in non-agricultural activities in northern Mozambique (n=645)

	Eastern part	Central part	Western part
Collecting firewood	99.0	100	97.1
Collecting domestic water	100	100	100
Fishing	10.7	8.6	7.2
Hunting animals	20.0	52.8	6.3
Gathering non-timber forest products	79.0	69.5	60.9
Operating non-farm businesses	64.9	32.6	42.5
Hired for agricultural labor	12.2	9.4	7.7

Source: Author

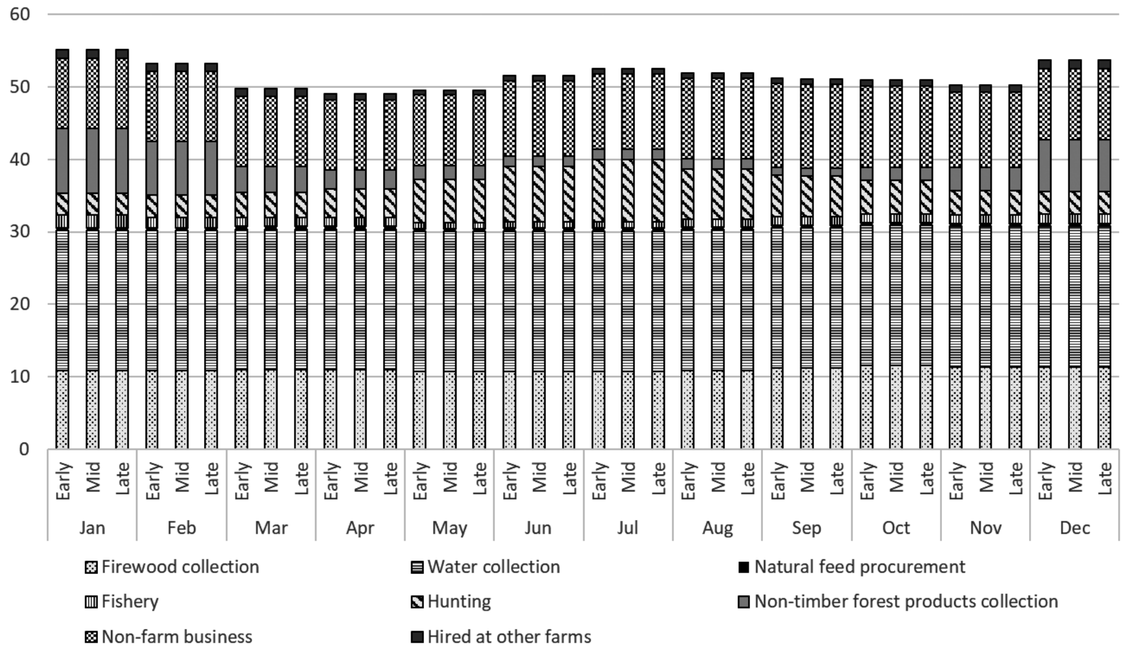

Figure 1. Average work hours by season for non-farm activities (Example for the central part)
Source: Koide et al., 2018

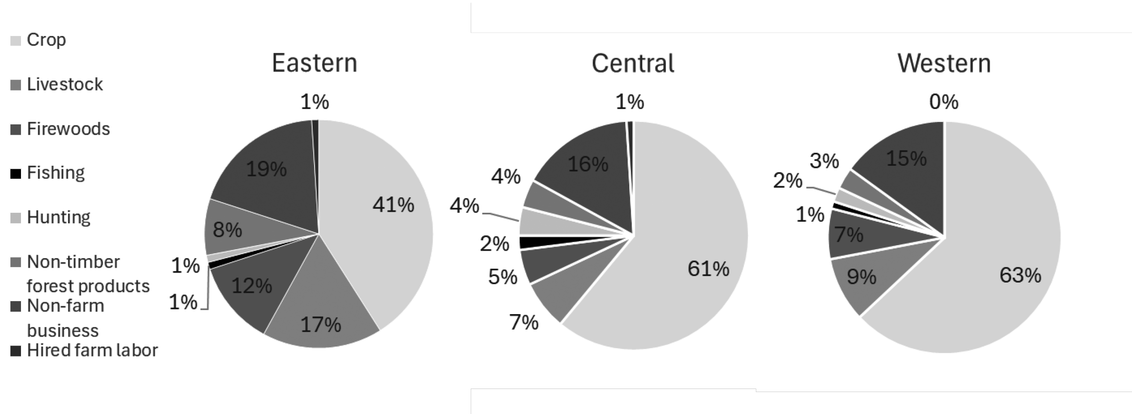

Figure 2. The composition and share of annual income among smallholder households across the surveyed areas.
Source: Author

4. Implications for the development of farm management models

As discussed above, the primary livelihood strategies of smallholders in SSA are characterized by diversified agricultural and non-agricultural economic activities. While the structure and scale of livestock production may vary, many smallholder farming communities commonly adopt strategies that derive a substantial portion of food and income from crop production. Risk management is integral to these strategies. In practice, many smallholders implement farming systems that meet household demands for food security and income by diversifying crop types and cropping patterns, thereby mitigating production and market risks. To maximize the outputs of such systems, it is essential to efficiently allocate the limited resources available to smallholders, including land and labor, across multiple competing production demands. Furthermore, these must encompass diverse cropping systems, including mixed and intercropping, which involve different crop combinations practiced by African smallholders. The design of farm management models capable of optimizing resource allocation across these multiple production demands holds great promise.

However, such design alone is insufficient to effectively support smallholders' decision-making. As illustrated by the survey results from northern Mozambique, many smallholders rely on both agricultural production and various non-agricultural activities for their diet and livelihood, such as collecting firewood and water, fishing, hunting, gathering, and operating non-farm businesses. Fish, meat, fruits, and other products obtained through fishing, hunting, and gathering play a crucial role in supplying households with essential nutrients not easily obtained from harvested crops, such as animal proteins and vitamins. Additionally, diverse non-farm businesses (e.g., trade, driving, crafting, sewing) serve as significant sources of cash income outside of agricultural production. Although smallholder production emphasizes risk hedging through diversification and mixed cropping, its reliance on rainfed agriculture risks the stable provision of household food and income. Therefore, by engaging in diverse non-farm activities alongside agricultural production, smallholders aim to enhance risk management and the stable securing of multiple sources of food and income across their entire livelihood. Consequently, labor allocation that significantly reduces non-agricultural income from its current level should be avoided. Conversely, substantially increasing the proportion of income from non-agricultural livelihoods is unrealistic, given the constraints on the quantity of natural and human resources on which these livelihoods depend. Within this framework, it is necessary to adjust labor allocation to minimize tradeoffs between farming and non-farming activities. Farm management models that facilitate this adjustment will serve as informative tools for meeting the livelihood goals and needs of smallholder households in SSA.

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1-2 Proposal for a multi-goal integrated farm management model to enhance smallholder decision-making in sub-Saharan Africa

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Abstract
Agricultural decision-support models based on mathematical programming are frequently employed to determine the economically optimal allocation of available resources to achieve desired farm objectives. However, efforts to develop a realistic, comprehensive, and easily applicable model that fully integrates the farm management strategies of African smallholders have been limited. This paper first reviews the major modeling approaches prevalent in the literature and subsequently proposes a comprehensive farm management model designed to more effectively support African smallholders in achieving their food security and livelihood goals. The proposed model's features include the capability to manage diverse cropping systems, encompassing not only monocropping but also mixed cropping and intercropping with various crop combinations—practices commonly adopted by African smallholders as a key risk management strategy in the face of fluctuating climate and market conditions. The model also ensures the fulfillment of food production demands aligned with household dietary preferences and derives optimal solutions to enhance overall income through efficient labor allocation, both within agricultural activities and between agricultural and non-agricultural pursuits. Furthermore, this paper discusses several applications of the proposed model with specific technological components to identify optimal technology choices and adoption strategies for smallholder farmers.

1. Introduction

Significant efforts are being made to establish and promote sustainable agricultural innovation to mitigate the persistent threats of food insecurity and poverty in sub-Saharan Africa (SSA). However, there remains a gap between developing and applying methods specifically designed to effectively assist farmers in making informed decisions, including the judicious adoption of these agricultural innovations. For such decision support to be practical, the expected benefits must be substantial enough to incentivize farmers, necessitating efficient use of farm resources to realize those benefits. Inefficiency in resource use, often resulting from suboptimal resource management decisions, has historically compromised agricultural performance in SSA (Mesike et al., 2009). Consequently, there is a pressing need for robust farm decision-support tools to enhance resource use efficiency; however, their development and application remain limited in SSA. Greater efforts should be directed toward promoting decision-support mechanisms for African farmers to efficiently utilize available resources.

Mathematical programming is one of the most promising techniques for addressing resource use inefficiency in agriculture. It can identify alternative solutions that fully exploit economies of scope and maximize whole-farm profits. This technique has long been recognized as pivotal in elaborating and applying operations research across civilian sectors. Computer-aided decision-support systems have been developed and employed for a range of optimization purposes, including transportation scheduling, land allocation, and production planning. Compared to heuristic decision trees—another informative tool often used in decision-making research—mathematical model-based optimization techniques offer several advantages. These include accommodating multiple input and output decisions, conducting sensitivity and tradeoff analyses, and providing clear policy recommendations that identify sources of economic inefficiencies (Schreinemachers and Berger, 2006). Leveraging these advantages, numerous studies have applied mathematical programming to address the inefficiencies of conventional farm resource use practices and compute optimal alternatives (Mellaku and Sebsibe, 2022). However, as discussed below, existing modeling frameworks are often inadequate to provide effective and beneficial decision support for smallholder farmers in SSA. This inadequacy stems from the limited integration of their highly diversified cropping systems and food production requirements, the timely allocation of labor resources between farm and non-farm activities, and the impact of these factors on livelihood outcomes. All these elements are essential for establishing a realistic and comprehensive decision-support model that fully incorporates the livelihood strategies of smallholder farmers.

This paper first reviews the significant opportunities and challenges of mathematical programming model-based farm decision supports in developing regions, including SSA. Based on the review findings and the whole-farm modeling implications identified in Chapters 1-1, a basic structure for an alternative farm management model is then proposed, designed to efficiently assist smallholders in achieving their goals, including food security and income enhancement. Finally, this paper outlines exemplary applications and extensions of the proposed model to identify optimal technology adoption under varying contexts of technical promotion.

2. Mathematical programming model-based farm decision supports in developing regions

Most mathematical programming models used to optimize agricultural resource allocation in developing countries fall into single-objective linear programming (LP) models, multi-objective goal programming (GP) models, fuzzy goal programming (FGP) models, or GIS-based mathematical models (Mellaku and Sebsibe, 2022). Regardless of the model type, studies highlight the advantage of model-based agricultural resource use decisions in achieving optimal results compared to conventional agricultural resource decision-making practices.

Numerous studies employ LP decision-support models that aim to maximize the economic performance of cropping patterns, livestock systems, and land and water resource use. Compared to single-objective LP models, multi-objective GP models are less frequently used. However, they are well-suited to addressing different sustainability goals, including economic and environmental objectives, by assigning equal or desired weights to the objectives. Studies employing GP have demonstrated its potential role in significantly improving agricultural performance without compromising the sustainable use of natural resources (e.g., Leung and Lung, 2007; Hassan et al., 2012; Pastori et al., 2017). For instance, the multi-objective model analysis by Pastori et al. (2017) indicates that in most African countries, farmers can significantly increase their income while preserving the environment by adopting efficient soil nutrient and water management strategies. However, deterministic parameter estimation used in both LP and GP models is contested, given the precarious nature of agriculture, which is subject to climate and market fluctuations (Pal and Moitra, 2004). To reflect the uncertainty in model parameter estimation, FGP models were developed to allow flexibility by considering the risk level of each goal that may arise from imprecise climate and market information (Pal and Moitra, 2004; Sharma et al., 2007). Studies employing FGP models conclude that they may yield better results than conventional deterministic decision-making approaches (Sharma et al., 2007; Rezayi et al., 2017). Following the evolution of respective mathematical models, a current trend in mathematical model-based decision research in agriculture combines these models with geographic information systems (GIS) (Mellaku and Sebsibe 2022).

Although many studies employing mathematical programming—be it LP, GP, FGP, or their variants—report a positive influence on agricultural decision-making, there are practical concerns about how farmers benefit from these models (Collins et al., 2013). Notably, the mathematical decision-support models have varied levels of complexity, timescale, technical capability requirements, and data demands. While GP, FGP, and GIS-based models are more informative than LP models, their relatively high programming and computational costs of treating numerous objectives and parameters significantly limit their practical use. Moreover, the reliable data required for multi-objective models, particularly those incorporating environmental risk variables, are limited or costly to acquire. Data procurement is even more challenging when employing such models for dynamic decision analysis that requires reliable time series or panel data sources. Besides substantial data requirements, fuzzy logic and GIS-integrated models demand more extensive technical skill and expertise than others (Mellaku and Sebsibe 2022). The high cost of acquiring specialized software to run these models is another key constraint to extending their application, especially in low-income countries. On the other hand, simple LP models serve as relatively adaptable decision-support tools that might be used immediately to optimize single-time decision outcomes with limited technical skill, employing existing secondary or primary data.

LP models are common in agricultural decision-support studies in SSA, providing valuable insights into the economic inefficiencies of conventional resource allocation in agriculture and the potential for profitability enhancement through optimal solutions. Since a common problem most farmers encounter when aiming to maximize profit is crop mix selection, many decision-support studies have applied the LP model to identify profit-maximizing crop mixes (e.g., Mohamad and Said, 2011; Felix et al. 2013; Otoo et al. 2015; Buzuzi and Buzuzi, 2018). However, their findings are often unconvincing due to the insufficient consideration of cropping options, including mixed and intercropping systems, diverse food self-sufficiency requirements, the efficient allocation of labor between farm and non-farm sectors, and the subsequent impact on livelihood performance.

In many regions of SSA, smallholder farmers employ mixed and intercropping systems as essential strategies to mitigate the risks inherent in rainfed agriculture and to secure multiple sources of food and income. Yet, studies exploring optimal crop mixes typically optimize the selection of monocropping systems without incorporating farmers' mixed and intercropping options into the model (e.g., Mohamad and Said, 2011; Buzuzi and Buzuzi, 2018). Regarding the efficient allocation of labor between farm and non-farm activities and its impact on livelihood outcomes, no optimization studies, to the best of our knowledge, have accounted for these factors. Notably, non-farm activities are often overlooked but are crucial in household modeling (van Wijk et al., 2012). Furthermore, previous model-based optimization studies have rarely integrated alternative technology components into their models. Consequently, there is a lack of decision support that can inform farmers on which technologies to adopt and on what scale, and the expected benefits they would bring. Given the significant role that innovative technologies can play in enhancing smallholder farm productivity and profitability, it is imperative to identify resource use strategies that optimally leverage these technologies to achieve smallholders' food security and income objectives.

3. Basic structure of a farm management model to support African smallholder decision-making

As emphasized in the previous chapter (Chapter 1-1), African smallholders adopt farming systems designed to mitigate production and market risks by diversifying crop types and cropping patterns while simultaneously addressing household needs for food security and income. Moreover, they engage in livelihood strategies that enhance risk management and ensure the sustainable provision of food and income by securing a variety of non-agricultural livelihoods. The African Smallholder Farm Management Model (ASFAM) has been developed to integrate these strategies. As depicted in Figure 1, this model incorporates farming conditions (farm size, number of family labor, and wages), farming indexes (cropping systems, technology, yields, prices, costs, and labor hours), subsistence conditions (types and quantities of subsistence crops), and non-agricultural activities (water fetching, firewood collection, hunting/gathering, and off-farm employment). The ASFAM is designed to ensure (1) securing food production areas based on household dietary preferences, (2) incorporating risk mitigation strategies such as mixed/intercropping, and (3) maximizing income through optimal labor allocation between agricultural and non-agricultural activities. It enables identifying optimal cropping systems that enhance overall household income and offer farm improvement strategies tailored to smallholder farmers' dietary needs, risk management, and non-farm activity requirements (Koide et al., 2019).

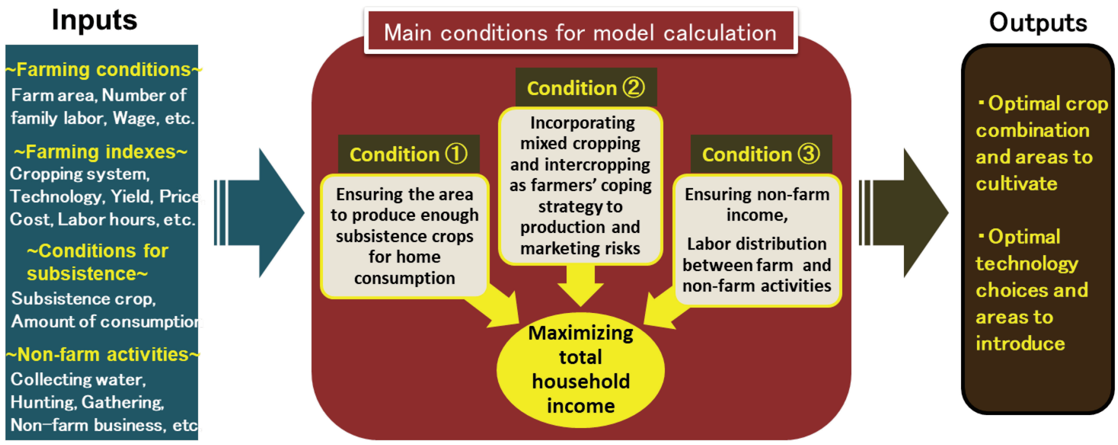

Figure 1. Schematic diagram of the basic structure of ASFAM

Following the above modeling framework, the basic structure of ASFAM is defined by the following single-objective linear programming, which simultaneously determines the optimal allocation of multiple farm resources to maximize the profitability of the entire cropping system while meeting household food self-sufficiency requirements.

$$\max Z = \sum_{i=1}^{m} c_i x_i$$

s.t.

$$\sum_{i=1}^{m} a_{ki} x_i \leq b_k, \qquad for\ all\ k$$

$$\sum_{i=1}^{m} d_{il} x_i \geq e_l, \qquad for\ all\ l$$

$$x_i \ \geq 0, \qquad for\ all\ i$$

where c_i is the net income of activity i, x_j is the area of activity i, a_{ki} is the technical coefficient that captures the level of use of resource k for activity i, b_k is available resource k, d_{il} is the yield of crop l from activity i, e_l is the household self-sufficiency requirement of crop l. i covers both farm and non-farm activities. k covers all types of farm resources to be considered, including farmland, which may be divided into several land categories (e.g., upland crops, lowland rice, and vegetable plots) and labor, reflecting the seasonality of family and hired labor inputs. In irrigation farming, water resources are included in *k*. Financial resource constraints may also be considered when the data are available. Crop *l* covers all edible crops used in each household, with e_l determined by the annual consumption of each crop.

The ASFAM has several unique features not found in traditional farm management models. One of these is the optimization of diverse cropping systems, including mixed and intercropping, contrasting with other models that focus on monocropping optimization. Additionally, the ASFAM addresses the efficient allocation of available labor between agricultural and non-agricultural activities and the consequent improvement of total household income. Despite the increasing importance of non-farm activities in household economies in SSA, this aspect has not been explicitly considered in current farm management models (van Wijk et al., 2012). While some studies have incorporated crop-specific subsistence requirements (e.g., Adesina and Ouattara, 2000; Igwe et al., 2013), they primarily focus on food self-sufficiency based on monocrop yields. The ASFAM, however, enables optimal calculations that meet farmers' food production demands based on the yields of each crop within mixed/intercropping systems, aligning more closely with the actual practices of smallholder farmers in SSA. Moreover, the ASFAM's structure is simple enough to be implemented in mathematical programming software that does not require specialized knowledge (or cost), making it accessible to non-researchers such as local agricultural extension agents. This enhances the model's applicability by facilitating technical guidance and decision support for potential local users (see Chapter 5-2).

The ASFAM is designed to simultaneously determine the optimal allocation of multiple resources, including land and labor (and other resources when available), to maximize household income—a primary livelihood objective for smallholders and a key indicator for practical decision support. Other economic metrics commonly used in mathematical programming-based farm management models, such as profit calculated by accounting for imputed costs (e.g., owned land and family labor costs) or utility measured by integrating various functions, are often challenging for smallholder farmers in SSA to comprehend and interpret. These metrics also demand relatively high data inputs and costs. Consequently, such measures are avoided in ASFAM to facilitate smoother model application and decision support for farmers. However, adjusting ASFAM to optimize resource allocation based on these metrics could be valuable for alternative purposes such as academic research. Furthermore, extending ASFAM into a stochastic simulation model that accounts for variations in crop yields and prices may be advantageous, aiming to maximize expected value or minimize the volatility of household income, profit, or utility.

4. Integration of technological components into the model

The ASFAM is fundamentally designed to identify the optimal configuration of multiple cropping options feasible for smallholders, the optimal adoption area for each cropping option, and the aggregate income derived from them. Additionally, if specific technologies are employed within these cropping options, the ASFAM can determine the adoption feasibility and the optimal adoption area for these technologies. For instance, consider the scenario where smallholder farmers in SSA gain access to chemical fertilizers—still limited in use—through governmental subsidies or technical guidance on fertilizer application. Development practitioners and local agricultural extension agents might want to know whether the target farmers should adopt cropping options involving chemical fertilizers to maximize overall profitability based on available resources and food requirements, and if so, to what extent. By incorporating the farm management indicators (yield, cost, and labor hours) of alternative cropping options involving the use of chemical fertilizers into the ASFAM, by either replacing or adding to those of conventional cropping options, it can determine the feasibility and optimal adoption area of such fertilized cropping options. An example of this model application will be presented in Chapter 2-2. Similarly, if there is an interest in guiding smallholder farmers in adopting a specific technology package—such as improved varieties or sowing methods coupled with chemical fertilizers—the ASFAM can identify the feasibility and optimal adoption area for such a package through similar data input and calculation processes.

The ASFAM can also be utilized to assess the feasibility and optimal adoption of technologies achievable by utilizing additional natural resources beyond the preexisting ones used in conventional agriculture. This involves extending the model constraints. For example, consider irrigation technologies. Agriculture in SSA largely relies on rainfed systems and is vulnerable to climate variability. Therefore, the development of irrigation technologies utilizing existing water resources like reservoirs has gained renewed attention for stabilizing crop productivity and profitability (Fox et al., 2005; Xie et al., 2014). However, even though SSA has substantial potential for irrigation, conventional irrigated agriculture practices are underdeveloped and often lack technical and input use efficiency (Nigussie et al., 2020). Therefore, it is imperative to provide decision support to farmers to efficiently utilize recommended irrigation technologies. Optimizing irrigation technology utilization necessitates explicitly incorporating the availability of water resources into the model alongside the resources of land and labor possessed by irrigation farmers. The availability of water resources, especially when sourced from reservoirs, is determined by hydrological conditions such as storage capacity and water balance. Furthermore, since reservoirs are often community-owned assets in SSA, the actual availability and allocation of water are practically regulated by social conditions, including customary rules, gender roles, and arrangements of local organizations, particularly water user associations. Thus, integrating these hydrological and social conditions into the modeling framework is crucial to appropriately analyze the feasibility and optimal adoption of irrigation technologies (Figure 2). Moreover, extending this integrated model into a stochastic simulation model, considering interannual variability in crop yields, production costs, and sale prices, allows evaluation of the stabilizing effects of irrigation technologies on the productivity and profitability of the entire cropping systems, thereby assessing their risk mitigation benefits. Chapter 3-2 will provide an example of such optimization of irrigation technology adoption considering risks.

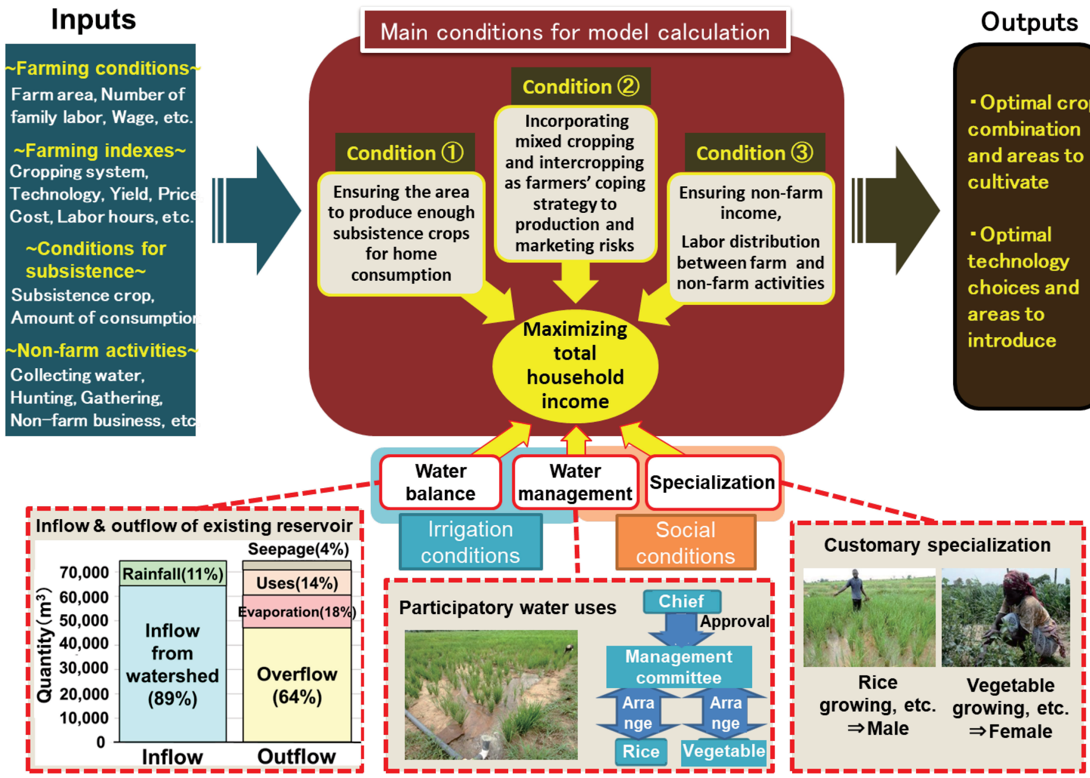

Figure 2. Schematic diagram of the extended ASFAM that integrates irrigation components

One might seek to enhance the ASFAM by incorporating new production sectors and determining the efficient resource allocation between these and the existing production sectors. In many cases, agriculture practiced by smallholders in SSA heavily relies on crop production. However, there is increasing emphasis on diversifying food, nutrition, and income sources, such as by promoting the introduction of valuable livestock like dairy cows. Moreover, in crop-livestock farming systems, the adoption of integration technologies—such as using crop residues as livestock feed or applying manure containing livestock excreta to crop fields—is essential for efficiently utilizing available farm resources and achieving desired outcomes, such as stable food and feed supply and income enhancement. The ASFAM can be expanded and applied to simultaneously optimize farm resource allocation between crop and livestock enterprises to maximize overall outcomes.

For example, Figure 3 presents a schematic diagram of a crop-livestock integrated management model that is an extension designed to derive optimal farm resource utilization for both cropping and dairy enterprises. The key optimization conditions added to this model include the animal composition and the feed supply-demand balance, both of which are necessary to sustain livestock production. The former condition is based on the composition ratio of animals at each growth stage that enables livestock reproduction, derived from factors such as calving intervals, accident rates, and rearing and production periods. The latter condition specifies the composition and quantity of feed and the nutrients required to achieve a certain level of livestock production. Among these feed compositions, the nutrient supply from self-produced feed is determined by the production of crop residues and forage. Consequently, the optimal cropping system can vary significantly depending on the relative productivity and profitability performance of different crop options, the nutrient supply required for the chosen livestock options, and their associated profitability. Additionally, among the optimal cropping area and livestock numbers simultaneously determined by the integrated farm management model, the latter must be an integer. Therefore, the model calculations rely on mixed-integer programming, in contrast to the linear programming used in models that solely optimize cropping systems. Chapter 4-2 presents an example of optimizing integrated farm management based on crop-dairy interactions using the ASFAM-based mixed-integer programming model.

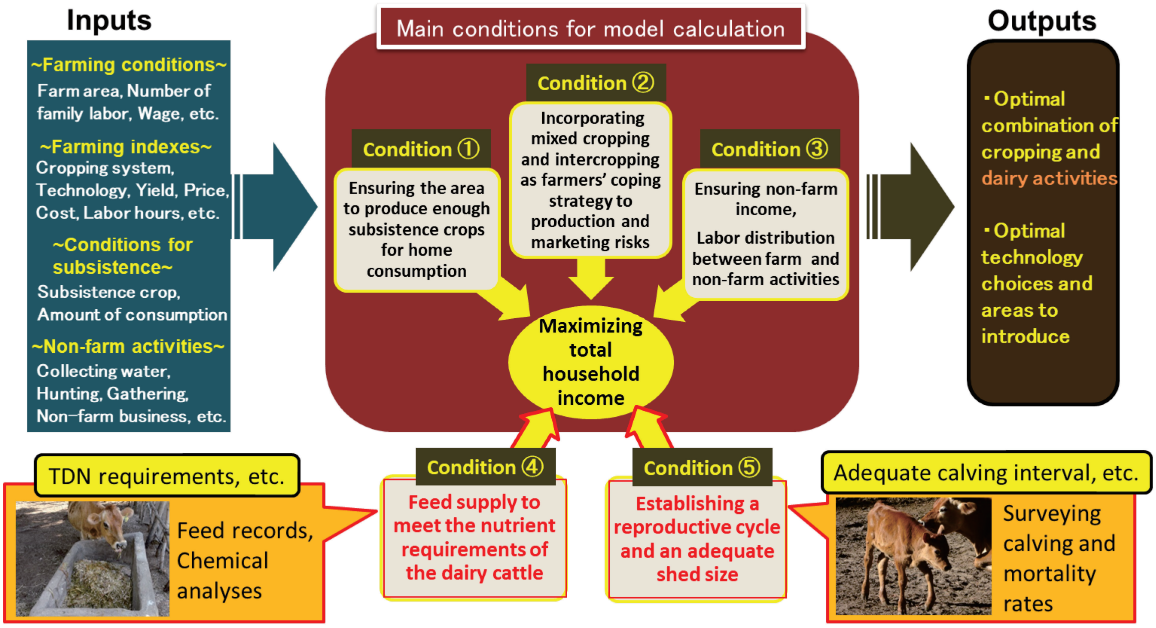

Figure 3. Schematic diagram of the extended ASFAM that integrates livestock components

5. Concluding remarks

This paper presents the development of a basic farm management model designed to support food security and income improvement among smallholder farmers in SSA. By applying ASFAM, it is possible to identify the optimal cropping solutions and their income-enhancing effects, which may effectively satisfy the needs of smallholder farmers. Moreover, by comparing these model outputs across multiple regions with differing agroecological environments and/or among various categories of farming households with distinct socioeconomic attributes (such as total farm size), it becomes feasible to pinpoint specific farm management issues that need to be addressed and to recommend tailored decision support for each region or household category. An example of such analyses is provided in the following chapter (Chapter 1-3).

This chapter discussed several examples of the application and extension of ASFAM aimed at identifying optimal technology adoption. From Chapter 2 to Chapter 4, research findings from various parts of SSA, obtained by applying models that incorporate additional technological components such as fertilization, irrigation, and crop-livestock integration, are presented. However, it is also possible to integrate other technological components into ASFAM and analyze optimal technology adoption and its effects on whole-farm benefits. The key strength of the proposed model lies in its fundamental and straightforward structure, which allows for easy extension and application in the development of optimal farming plans utilizing various technology options.

The farm management model proposed in this chapter is designed to efficiently address the multiple livelihood strategies currently employed by smallholder farmers in SSA. However, since these strategies may evolve, it is essential to apply the model in a way that allows for flexible adjustments to parameters and the types and weights of objectives considered within the model rather than constraining them in a deterministic manner. For instance, if the penetration of market economies in SSA leads to an increase in farmers pursuing more commercial-oriented agriculture, it will be crucial to recalibrate optimal farm management by carefully adjusting the weightings of updated food security and income objectives. The application of such adaptive modeling has not been thoroughly explored in this chapter and should be addressed in future research.

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1-3 Cropping system optimization and diagnoses using an African smallholder farm management model: Case of northern Mozambique

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Abstract

A critical factor limiting agricultural performance in Africa is the suboptimal management practices commonly observed among farmers. This chapter explores optimal farm management strategies across the three agroecological zones of northern Mozambique, building on research by Koide et al. (2018). Employing a mathematical programming-based farm management model tailored to mitigate economic inefficiencies in resource allocation among competing production demands, the study identifies ideal cropping systems that effectively enhance food security and maximize income. Findings indicate that crop diversification in upland areas significantly increases income in regions facing substantial production and market risks. Furthermore, the study highlights the benefits of expanding production of the most profitable beans and tubers specific to each zone, in addition to primary food staples, to enhance income and food self-sufficiency, particularly for farmers with over 1 hectare of land. For farmers with less than 1 hectare, expanding their cultivated area proves advantageous, a viable strategy given the current availability of land and labor. Nevertheless, at current productivity levels, the next generation may experience significant food shortages due to reduced farm sizes stemming from land fragmentation through inheritance. Consequently, prioritizing research on optimal cropping systems that enhance land-use efficiency is essential.

1. Introduction

Agriculture in sub-Saharan Africa (SSA) is predominantly characterized by small family farms operating on limited hectares of land (Jayne et al., 2014). These farms combine semi-subsistence and semi-commercial agriculture, cultivating crops primarily for household consumption while marketing their surplus and commodity crops (Koide et al., 2016). Nonetheless, they face numerous challenges that hinder food security and income enhancement, including heightened production risks associated with climate change, volatile market conditions, insufficient access to information, and credit limitations. To mitigate these issues, a variety of technological and institutional solutions are explored, with an increasing volume of empirical studies investigating adoption dynamics, constraints, and impact factors, thereby informing policy. Despite these advancements, the suboptimal farm management practices, which could significantly undermine the effectiveness of technological and institutional interventions, are infrequently addressed. Given that agricultural resource utilization by farmers in SSA is traditionally inefficient (Mesike et al., 2009), it is imperative to explore optimal resource use strategies that enable efficient attainment of food security and income objectives.

Mathematical programming-based decision-support models are valuable for identifying the economically optimal allocation of available resources to achieve specified farm objectives (Mellaku and Sebsibe, 2022). In SSA, existing modeling efforts have explicitly focused on maximizing agricultural income alongside key strategic factors for smallholder farming, including food self-sufficiency and risk aversion (e.g., Igwe and Onyenweaku, 2013; Nyikal and Kosura, 2005). However, in contemporary SSA, the relative importance of the agricultural sector in rural livelihoods is declining due to population growth and diminishing arable land, compelling farmers to increasingly depend on the non-farm sector. Consequently, enhancing total household income, including farm and non-farm sources, is a critical issue requiring attention. Another significant issue in whole-farm modeling is the inadequate representation of the farm. Most previous studies in SSA employing farm management models have constructed models for specific farms, with selection criteria often insufficiently justified. Given the highly heterogeneous socioeconomic and biophysical contexts in African agriculture, generalizing findings from such farm-specific models is challenging. Therefore, it is essential to utilize a model that adequately considers regional characteristics and the representativeness of farming conditions.

This chapter presents the study conducted by Koide et al. (2018), which addresses these issues. It investigates optimal resource utilization strategies to achieve key development objectives in African agriculture under representative farm conditions across various regions with distinct production environments. Specifically, it highlights optimal cropping systems that are most effective in securing food and maximizing income for smallholder households in the three agroecological zones of northern Mozambique.

2. Materials and methods

2.1 Data

Koide et al. (2018) designated the Nacala Corridor in northern Mozambique as the locus of their study. The Nacala Corridor is recognized as a critical hub for agricultural development in southern Africa due to its substantial agricultural production potential, attributable to its advantageous soil and climate. The production environment exhibits considerable variability, ranging from the semi-arid coastal regions in the east to the relatively high-rainfall inland highlands in the west. Consequently, this study concentrates on the rural areas of Nampula, Gurue, and Lichinga (designated as the eastern, central, and western regions, respectively), which are principal cities along the Nacala Corridor (JICA, 2010). Data were acquired through farm household surveys conducted in these three areas. A total of

645 farm households were randomly selected (205 from the eastern region, 233 from the central region, and 207 from the western region), with 30–40 households per village being surveyed, depending on village size. Interviews were conducted in the local language using a structured questionnaire to collect data on household farm management and livelihood status. The survey took place in 2016, following a two-year preliminary survey (2014–2015) during which the questionnaire was systematically refined. The survey was executed by university students specializing in agriculture, who served as field enumerators. These enumerators underwent preliminary training and testing under the supervision of researchers from the National Institute of Agricultural Research of Mozambique to ensure the consistency and accuracy of data collection. For comprehensive data on yields, prices, labor, and other critical variables for each crop, three years of data (2014–2016) were collected. Farmers were provided with farm-specific record forms annually, and data were accumulated through periodic inspections and guidance. Furthermore, field visits were conducted to verify all cultivated crops, planted areas, and harvested products to accurately capture farmland size, cropping systems, and yields (Koide et al. 2018).

2.2 Analysis

Using the African Smallholder Farm Management Model (ASFAM) detailed in Chapters 1-2, the optimal cropping solution was computed for farms incorporating representative cropping options and non-farm activities within each region. All constraints and processes within the model are derived from actual survey data specific to each region. Land constraints were classified into lowlands and uplands based on local land-use patterns. Labor conditions were established considering the farmers' lifestyle and work performance, including the number of days available for farming (specifically 9 days every 10 days, accounting for religious activities) and daily work hours (specifically 10 hours per day, according to actual work records). Up to five temporary workers could be employed, with the average regional unit cost per hour as the employment expense. The cropping options comprised crops and cropping patterns typical of each region, with profit and technical coefficients set according to average income, costs, labor hours, and other variables. Adhering to the ASFAM framework, food self-sufficiency constraints were incorporated, reflecting the demand for major food staples in each region. An additional component allowed for allocating labor between farm operations and non-farm activities based on labor performance in various non-farm sectors. The model is not designed to optimize livestock enterprises and their integration with cropping sectors simultaneously with the cropping component due to the relatively small scale and limited significance of livestock at the study sites. However, the labor demands for current natural feed procurement were taken into account to sustain existing livestock production levels (Koide et al., 2018).

Since the calculated optimal cropping solutions may vary depending on farm size, solutions were computed for small farms (less than 1 hectare), medium-sized farms (1–2 hectares), and large farms

(2 hectares or more). The anticipated impact of the optimal solutions for each category was assessed by comparing them with the current food supply and income levels. Finally, the opportunities and challenges associated with the cropping solutions were discussed, with particular emphasis on the effects of increasing land fragmentation (Koide et al., 2018).

3. Results

Table 1 delineates the cropping solutions derived from the model. In the eastern region, sweet potatoes are grown in lowland areas due to their substantial profitability, whereas mixed cropping of cereals and legumes, both highly profitable and essential food sources, is adopted in upland areas. Notably, multi-crop mixed cropping, including the commercially significant groundnut, becomes increasingly dominant as farm size grows. In the central region, rice is cultivated in lowland areas, while monocultures of staple crops such as maize and sorghum, along with mixed cropping of pigeon pea, are prevalent in upland areas. As farm size increases, soybeans emerge as the predominant crop due to their high profitability. In the western region, staple crops like maize and common beans are intercropped, and the highly profitable sweet potato monoculture is also implemented, expanding with increasing farm size. Coastal areas (eastern regions) are particularly vulnerable to drought and other environmental damage, as well as to price declines due to overproduction. The cropping strategy in the eastern regions is characterized by a pronounced risk-hedging approach, involving the cultivation of a diverse array of subsistence and cash crops to mitigate production and market risks (Koide et al. 2018).

Table 1. Model-based cropping solutions by region and farm size

		Small-scale	Medium-scale	Large-scale
Eastern	Total farmland (ha)	0.68	1.44	3.05
	Cassava+Maize+Cowpea mixed	0.63	0.67	0.00
	Cassava+Maize+Cowpea+Groundnut mixed	0	0.69	2.92
	Sweet potato mono	0.05	0.08	0.13
	Achieving food self-sufficiency	No	Yes	Yes
Central	Total farmland (ha)	0.67	1.44	3.60
	Maize mono	0.29	0.48	0.54
	Sorghum mono	0.03	0.42	0.47
	Sorghum+Pigeon pea mixed	0.32	0	0
	Soybean+Pigeon pea mixed	0	0.54	2.59
	Rice mono	0.03	0.04	0.02
	Achieving food self-sufficiency	No	Yes	Yes
Western	Total farmland (ha)	0.71	1.49	3.90
	Maize+Common bean mixed	0.65	0.85	0.95
	Sweet potato mono	0.06	0.64	2.95
	Achieving food self-sufficiency	Yes	Yes	Yes

Note: The cropping solution for the small farms in the eastern and central parts shows the estimates that target maximum food self-sufficiency.
Source: Koide et al., 2018

A notable observation is that small farms in the eastern and central regions lack sufficient land to produce the necessary quantity of food crops, making self-sufficiency a significant challenge. This is not unexpected given that most farm households are not self-sufficient in food production and thus compensate by purchasing food. Specifically, small farms generally have fewer household members and consume less food independently; however, as illustrated in Table 2, they purchase food to the same extent, or even more, than medium and large farms. In light of this, achieving complete food self-sufficiency with constrained land and labor resources is challenging. Nonetheless, specializing in highly profitable crop production while purchasing additional food does not align with the subsistence objectives of the farmers. Consequently, among the optimal crop compositions detailed in Table 1, those for small farms in the eastern and central regions were designed to achieve the highest possible self-sufficiency ratio. Specifically, the required supply of major food crops was reduced to a level that can be met within the constraints of current farm resources and crop yields. This threshold level, accounting for 63% of household consumption in the east and 74% in the west, was established as the self-sufficiency constraint (Koide et al. 2018).

Table 2. Comparison of farm economies at present and when the cropping solution is introduced

		Eastern			Central			Western		
		Small-scale	Medium-scale	Large-scale	Small-scale	Medium-scale	Large-scale	Small-scale	Medium-scale	Large-scale
Present	Income (Mt)	17,113	25,585	55,614	11,010	27,390	79,440	19,820	34,832	62,041
	Food expenses (Mt)	2,719	2,900	2,839	2,066	1,569	2,347	1,849	1,725	2,273
	Income - Food expenses (Mt)	14,394	22,685	52,775	8,944	25,821	77,093	17,971	33,107	59,768
Model-case introduced	Income (Mt)	19,316	42,974	95,642	11,576	37,997	139,806	17,946	43,078	111,635
	Food expenses (Mt)	3,639	0	0	3,447	0	0	0	0	0
	Income - Food expenses (Mt)	15,677	42,974	95,642	8,129	37,997	139,806	17,946	43,078	111,635

Note: Food expenses are the total amount purchased, borrowed, and received, for example.
Source: Koide et al., 2018

However, in such instances, the income of small farms should not be directly compared to that of medium and large farms that have already attained food self-sufficiency. Furthermore, since many farmers are currently not self-sufficient, the cost of food supplementation ("food expense") must be subtracted from the income when comparing the current farm economy with the cropping solution. As shown in Table 2, there is no significant difference in the calculated values (Income − Food expenses) between the present and model-based cropping patterns for small farms, indicating that the actual household economic impact of adopting model-based solutions is minimal. Conversely, for medium and large farms, income will increase substantially, and food expenses will decline due to the achievement of food self-sufficiency. For the farmers in impoverished areas of SSA, where housing, utilities, and water costs are negligible, and expenditures on clothing and healthcare are minimal, food expenses comprise most of the household spending. Consequently, reducing food costs will markedly enhance the economic surplus of farm households (Koide et al., 2018).

Another significant effect of the cropping solution is the reduction in labor input. Although not explicitly indicated in Table 1, the cropping solutions for all regions and farm categories do not require hired labor. Given that hired labor costs constitute a large share of current farm management expenses across all regions, achieving income improvements without relying on hired labor is immensely important. If small farms adopt the cropping solution, although they may not experience a substantial rise in income or economic surplus, they can avoid the risk of income loss due to insufficient funds for purchasing inputs or work delays, compared to the current management model reliant on hired labor. Even if the direct economic benefits are limited, stabilizing income through risk mitigation could be a rational management strategy for small farms with limited savings (Koide et al., 2018).

While the effects of introducing the cropping solution have been discussed thus far, it is essential to assess them within the context of farm management and the entire livelihood. Figure 1 depicts the current income structure and the projected income increase following the introduction of the cropping solution. At present, the livelihood structure of small farms is more dependent on livestock production and non-farm activities. This trend is particularly evident in the eastern region, where income disparities in the cropping sector are less pronounced than in other regions. As a result, total income in the eastern region is the highest among small and medium farms. However, in large farms, the gap with the central and western regions, where cropping sector income holds greater weight, narrows considerably, and the two regions reach near parity. Under these circumstances, if the model-based cropping solution is implemented, total income for the medium group is projected to increase by 24%, 22%, and 13% in the eastern, central, and western regions, respectively, and by 40%, 54%, and 57% for the large group in the same regions. These variations in income growth across farm sizes are attributed mainly to the scale of adoption of high-profit crops, which is predicated on the assumption of food self-sufficiency. Conversely, regional differences in the income growth effect—i.e., the decreasing effect from the eastern to western regions for small and medium farms and the increasing effect for large farms—are linked to the characteristics of the cropping solution itself. Specifically, as farm size decreases, the income-enhancing effect of the cropping solution, which emphasizes greater risk dispersion (particularly in multi-crop mixed cropping systems in the eastern region), becomes more pronounced. This suggests that the cropping solution is advisable for improving the incomes of small farms that prioritize comprehensive risk management (Koide et al., 2018).

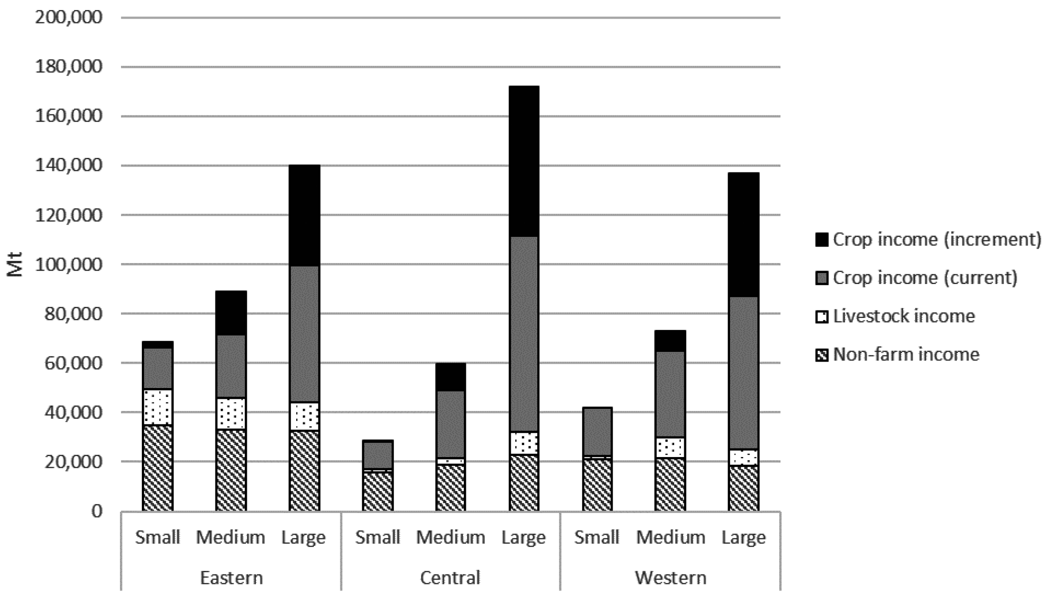

Fig. 1. Increase in household income by introducing the cropping solutions

Notes:

1) Small, Medium, and Large denote small, medium, and large farms, respectively.

2) Crop income is divided into the current income (current) and the increased income (incremental) due to the introduction of the cropping solution.

3) Non-farm income is the sum of income from hunting, fishing, gathering (firewood and non-timber forest products), agricultural hired labor, and off-farm employment.

Source: Koide et al., 2018

The preceding analysis explored the potential for enhancing farm management and livelihoods by implementing the cropping solution. However, while there is a possibility that small farms, in particular, may achieve more secure production by reducing their reliance on hired labor, the economic benefits will not be as substantial as those realized by medium and large farms. Moreover, it is conceivable that medium and large farms may eventually move toward reducing the size of their operations for the reasons described below.

Since land leasing or purchasing is uncommon across all regions, the only feasible way to expand cultivated land is by utilizing uncultivated areas (excluding fallow land). For small farms, the average area of uncultivated land is 0.88 hectares in the eastern region, 0.51 hectares in the central region, and 0.54 hectares in the western region. If these lands were converted to cultivated land, the optimal crop composition for small farms (Table 3) would align more closely with that of medium farms (Table 1), enabling them to attain food self-sufficiency and subsequently increase their income. However, these attainments cannot be indefinitely guaranteed in the long term due to a reduction in per-capita land holdings at the study site caused by the division and inheritance of farmland. Many farmers originally acquired land through allocations from local traditional authorities or by cultivating unclaimed land. Recently, however, changes in the role of traditional authorities and population growth have led to farmland being increasingly divided among household members, with inheritance primarily from fathers, resulting in smaller individual landholdings. This trend is expected to persist, as indicated in Table 4, where most farmers in all regions intend to divide and pass on their land to more than one child. Furthermore, since inheritance intentions are relatively uniform among farm households, landholdings will likely continue to shrink, regardless of current farm size. In fact, projections of land available for the next generation, based on inheritance intentions and household composition, suggest that most farm households will experience a reduction in land area from current levels, even if all uncultivated land is converted to cultivated land (Koide et al., 2018).

In such scenarios, the optimal cropping patterns (Table 4) indicate that small farms in the eastern and central regions, as well as small farms in the western region and medium farms in the central region—which previously had the potential to achieve food self-sufficiency—will face challenges in doing so. Consequently, they will be forced to revert to subsistence farming, resulting in a decline in income compared to the present situation (Table 2). For large farms, while food self-sufficiency may still be attainable, a marked reduction in income is nonetheless inevitable (Koide et al., 2018).

Table 3. Estimation of optimal cropping systems among small farms assuming the expansion of farmland

Eastern	Total farmland (ha)	1.56
	Cassava+Maize+Cowpea mixed	0
	Cassava+Maize+Cowpea+Groundnut mixed	1.51
	Sweet potato mono	0.05
	Achieving food self-sufficiency	Yes
	Income (Mt)	48,788
Central	Total farmland (ha)	1.18
	Maize mono	0.40
	Sorghum mono	0.34
	Sorghum+Pigeon pea mixed	0
	Soybean+Pigeon pea mixed	0.41
	Rice mono	0.03
	Achieving food self-sufficiency	Yes
	Income (Mt)	29,506
Western	Total farmland (ha)	1.25
	Maize+Common bean mixed	0.65
	Sweet potato mono	0.60
	Achieving food self-sufficiency	Yes
	Income (Mt)	36,774

Source: Koide et al., 2018

Table 4. Farmers' intention to inherit farmland and estimation of optimal cropping systems assuming available farmland size at the next generation

			Small-scale	Medium-scale	Large-scale
Eastern	Heir	All children (%)	61.1	74.5	70.2
		Some children (%)	22.2	9.6	17.5
		Other (%)	16.7	16.0	12.3
	Available farmland size at the next generation (ha)		0.73	1.25	2.09
	Optimal solution	Cassava+Maize+Cowpea mixed	0.68	1.03	0
		Cassava+Maize+Cowpea+Groundnut mixed	0	0.15	2.00
		Sweet potato mono	0.05	0.07	0.09
		Achieving food self-sufficiency	No	Yes	Yes
		Income (Mt)	20,695	35,773	65,546
		Food expenses (Mt)	3,142	0	0
		Income - Food expenses (Mt)	17,553	35,773	65,546
Central	Heir	All children (%)	48.1	41.3	43.5
		Some children (%)	36.7	44.6	48.4
		Other (%)	15.2	14.1	8.1
	Available farmland size at the next generation (ha)		0.65	0.84	1.76
	Optimal solution	Maize mono	0.29	0.38	0.54
		Sorghum mono	0.04	0.06	0.47
		Sorghum+Pigeon pea mixed	0.29	0.38	0
		Soybean+Pigeon pea mixed	0	0	0.74
		Rice mono	0.03	0.02	0.01
		Achieving food self-sufficiency	No	No	Yes
		Income (Mt)	11,030	13,979	48,206
		Food expenses (Mt)	3,889	3,702	0
		Income - Food expenses (Mt)	7,141	10,277	48,206
Western	Heir	All children (%)	71.9	71.6	71.3
		Some children (%)	12.6	14.8	13.8
		Other (%)	15.5	13.6	14.9
	Available farmland size at the next generation (ha)		0.60	1.11	1.98
	Optimal solution	Maize+Common bean mixed	0.60	0.85	0.95
		Sweet potato mono	0	0.26	1.03
		Achieving food self-sufficiency	No	Yes	Yes
		Income (Mt)	14,652	29,812	59,186
		Food expenses (Mt)	1,446	0	0
		Income - Food expenses (Mt)	13,206	29,812	59,186

Note: Maximum available land is projected assuming that all uncultivated land will be inherited and converted to cultivated land.

Source: Koide et al. 2018

5. Conclusion

Building on the research by Koide et al. (2018), this chapter outlines optimal cropping systems that are most effective in ensuring food security and maximizing income for smallholder households across the three agroecological zones of northern Mozambique. In the eastern region, where production and market risks are more pronounced, a diversified production strategy based on mixed cropping of upland crops is recommended. Households with relatively larger landholdings are advised to expand the cultivation of high-value commercial crops such as legumes (groundnuts in the east, pigeon pea in the central region) and tuber crops (potatoes in the west) while simultaneously achieving self-sufficiency in staple grains.

The optimal cropping solution enables small farms (with less than 1 hectare of farmland) to stabilize their operations by minimizing reliance on hired labor, though the proportion of subsistence crop production remains high, and their income remains nearly unchanged. Meanwhile, medium and large farms (with operational areas of 1 hectare or more) are projected to attain food self-sufficiency and increase the production of highly profitable crops, thus boosting their income and economic surplus, and improving their overall livelihoods.

These economic benefits align with strategic priorities essential for African smallholders—such as risk management, food self-sufficiency, and livelihood diversification—suggesting that these advantages may extend to many farm households, potentially stimulating the revitalization of the local economy. Notably, if small farms can achieve similar economic outcomes as medium and large farms, revitalizing the local economy becomes more achievable, given that small farms possess sufficient uncultivated land and labor to expand their production areas to 1 hectare or more.

However, even under these favorable scenarios, there is a significant risk that the next generation of farmers may face substantial reductions in cultivated land and income due to the division of land through inheritance. Without significant productivity improvements, some farmers—especially those operating small and medium farms—may struggle to achieve even basic food self-sufficiency. Therefore, it will be imperative to develop and evaluate farm management strategies characterized by cropping systems and technologies that offer higher land-use efficiency (Koide et al., 2018).

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Chapter 2 Issues and model-based optimization of smallholder technology adoption in upland cropping systems: Case of fertilization technology in central Burkina Faso

2-1 Suboptimal performance of farmers' NPK fertilizer application in the upland cropping systems of central Burkina Faso

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Abstract

A growing body of literature has evaluated the optimal application rates of inorganic fertilizers and their impact on major staple crops such as maize in sub-Saharan Africa. However, farmers' limited adoption and effectiveness of fertilizers, particularly for key upland crops other than maize, has not been adequately investigated. Using data from a multi-season survey of smallholder crop production in central Burkina Faso, this paper examines the yield response to farmers' NPK fertilizer application and its cost-effectiveness compared to non-fertilization for sorghum and cowpea, two vital local food and cash crops. The findings reveal that farmers experienced yield responsiveness to compound fertilizer for sorghum and cowpea during seasons with relatively favorable rainfall. However, similar responsiveness was not observed in seasons with poor rainfall. In neither season was the net income of the fertilized crops found to be superior to that of the non-fertilized crops. Due to limited fertilizer use efficiency, the yield gains appear insufficient to offset the cost of fertilizers, regardless of some rainfall variability. Nevertheless, our analysis suggests that significant increases in net income cannot be achieved solely by reducing fertilizer costs; substantial yield improvements are also necessary. Therefore, in addition to fertilizer price reduction measures such as subsidies, innovative strategies are needed to enhance profitability and incentivize farmers' fertilizer investments, including the implementation of effective agronomic practices that complement fertilization and marketing approaches designed to boost crop sales.

1. Introduction

Soil fertility management is crucial for enhancing agricultural productivity in sub-Saharan Africa (SSA), where nutrient deficiencies severely constrain crop yields and contribute to declining per-capita food production. The region's soils are often characterized by inherently low natural fertility, necessitating the effective use of fertilizers to sustain or improve soil nutrient levels and support sustainable agricultural practices. However, sole reliance on organic amendments poses challenges due to their limited availability and the logistical constraints of transportation. Consequently, applying inorganic fertilizers, such as NPK (nitrogen, phosphorus, potassium), is widely promoted to overcome soil fertility constraints and increase crop productivity.

Despite the recognized importance of inorganic fertilizer use, several challenges impede its effective implementation. The high cost of fertilizers remains a significant barrier for smallholder farmers in SSA, limiting their capacity to apply adequate quantities for optimal yields. Even when fertilizers are applied at recommended levels, farmers may experience unexpectedly low agronomic performance. Studies have documented "non-responsiveness," where fertilizer application at recommended rates fails to produce satisfactory yield gains (Roobroeck et al., 2021). Empirical evidence shows that the yield response to inorganic fertilizers in SSA often falls below expectations in farmers' fields, leading to suboptimal profitability (Burke et al., 2020).

Although numerous studies have assessed fertilizer use efficiency and the agronomic and economic performance of major food staples, primarily maize (e.g., Burke et al., 2019; Dabessa Iticha et al., 2021; Kiwia et al., 2022), relatively few on-farm investigations have evaluated the actual productivity and profitability gains achieved by farmers using fertilizers for other upland food and cash crops. In the extensive dryland areas of SSA, which are less suitable for maize production, there is a need to focus on investments in more drought-tolerant cropping systems. For instance, in the Sahel, farmers predominantly cultivate other cereals, such as sorghum, and legumes, such as cowpea, as their primary food and income sources. Given the severe impact of soil erosion and nutrient depletion on their production, judicious fertilizer application is vital for mitigating food and income insecurity in this region. However, the responsiveness and cost-effectiveness of fertilizers for these dryland crops in farmers' fields remain underexplored in the literature. To address this knowledge gap, further research is needed to investigate the constraints of fertilizer input and output in dryland environments.

Based on detailed multi-season production surveys of Sahelian cropping systems in central Burkina Faso, this paper aims to highlight trends in farmers' fertilizer selection and targeted crops and to examine the yield and profitability effects of fertilization across seasons. It clarifies significant challenges in actual fertilizer use and proposes promising interventions to support farmers in adopting and expanding fertilizer applications.

2. Materials and methods

We conducted an exhaustive field survey encompassing 237 plots cultivated by 20 randomly selected smallholder farm households in the rural area of Saria, located in the Boulkiemde province, Centre-Ouest region of Burkina Faso, over two consecutive years (2019 to 2020 cropping seasons). We visited all plots in both seasons and directly measured the cultivated area and crop harvests for accurate yield evaluation. Additionally, to collect accurate data on field crop management, we instructed every household to measure and record daily amounts and costs of inputs (seeds, fertilizers, herbicides, and insecticides) used and the number of persons, hours, and wages paid for each crop production activity, by providing measurement and recording materials along with careful instructions on their use. Our field staff regularly monitored and assisted with the measurement and recording activities and cross-checked the data before we double-checked it for approval. This elaborate data collection and inspection procedure was adopted primarily to avoid issues of farmers' recall and measurement errors. These issues have been found to undermine the reliability of agricultural output, input, and productivity variables (Wollburg et al., 2021).

Using the collected data, this chapter first discloses farmers' actual use of fertilizers, focusing on the most commonly used fertilizer in the study area. We highlight the application area, application rates, and target crops across two cropping seasons characterized by contrasting rainfall regimes: relatively favorable rainfall in the 2019 cropping season and unfavorable rainfall in the 2020 cropping season. Next, the relationship between fertilizer application rates and yields of the target crops is examined. The results of the two cropping seasons are compared to better understand the influence of rainfall variability on fertilizer use intensity and responsiveness. We also evaluate crop yields and profitability between fertilized and non-fertilized fields to underscore the advantages (or disadvantages) of actual fertilizer use. Additionally, the fertilizer prices or yields at which the profitability of fertilized plots significantly surpass that of unfertilized plots will be examined.

3. Results

The primary fertilizer farmers use at the study site is imported NPK compound fertilizer (mostly 14-23-14 and 15-15-15). A few farmers apply limited quantities of animal dung or manure to the homestead plots. Although the application of NPK fertilizer is the principal means for farmers to improve or maintain soil fertility, only 21.4% of the total cultivated area received this fertilizer in 2019 and 15.7% in 2020 (Table 1). Notably, nearly 90% of the fertilized crop fields were dominated by cowpeas. Given that cowpeas are one of the major cash crops in the study site, it appears that farmers aim to enhance income by concentrating fertilizer investment on this crop. This underscores the critical importance of examining the economic return on fertilizer use in the study site alongside agronomic response. The average application rates of NPK fertilizer on cowpeas were 94.6 kg/ha in 2019 and 41.6 kg/ha in 2020, both below the recommended application rate of approximately 100 kg/ha (Omoigui et al., 2018). Notably, the area and rate of application were relatively low in 2020, a year with less rainfall than 2019, even though the fertilizer prices in those two years were comparable. This suggests that farmers may have adjusted fertilizer use in response to rainfall conditions. The cropping systems for cowpeas are grown mainly by monocropping or mixed cropping with sorghum, a major staple food in the study site.

Table 1. NPK fertilizer application by farmers in 2019–2020 cropping seasons

	2019	2020
Percentage of NPK fertilized area in total cultivated area	21.4	15.7
Percentage of cowpea area in NPK fertilized area	89.6	85.3
Avg. application rate of NPK fertilizer in cowpea fields (kg/ha)	94.6	41.6

For NPK fertilizer application rates and grain yields in cowpea monoculture and mixed cropping with sorghum, both cowpea and sorghum yields increased with the rate of fertilizer applied in 2019 when sufficient rainfall was received, but not in 2020 when rainfall was relatively scarce (Figure 2). These results indicate varying yield responses to fertilizer under different rainfall conditions. However, even in 2019, when rainfall conditions were relatively favorable, the average yield of fields where NPK fertilizer was applied was not substantially higher than those without fertilizer. For instance, in cowpea monoculture, the average yield of fertilized fields was 510 kg/ha, slightly higher than that of unfertilized fields (458 kg/ha).

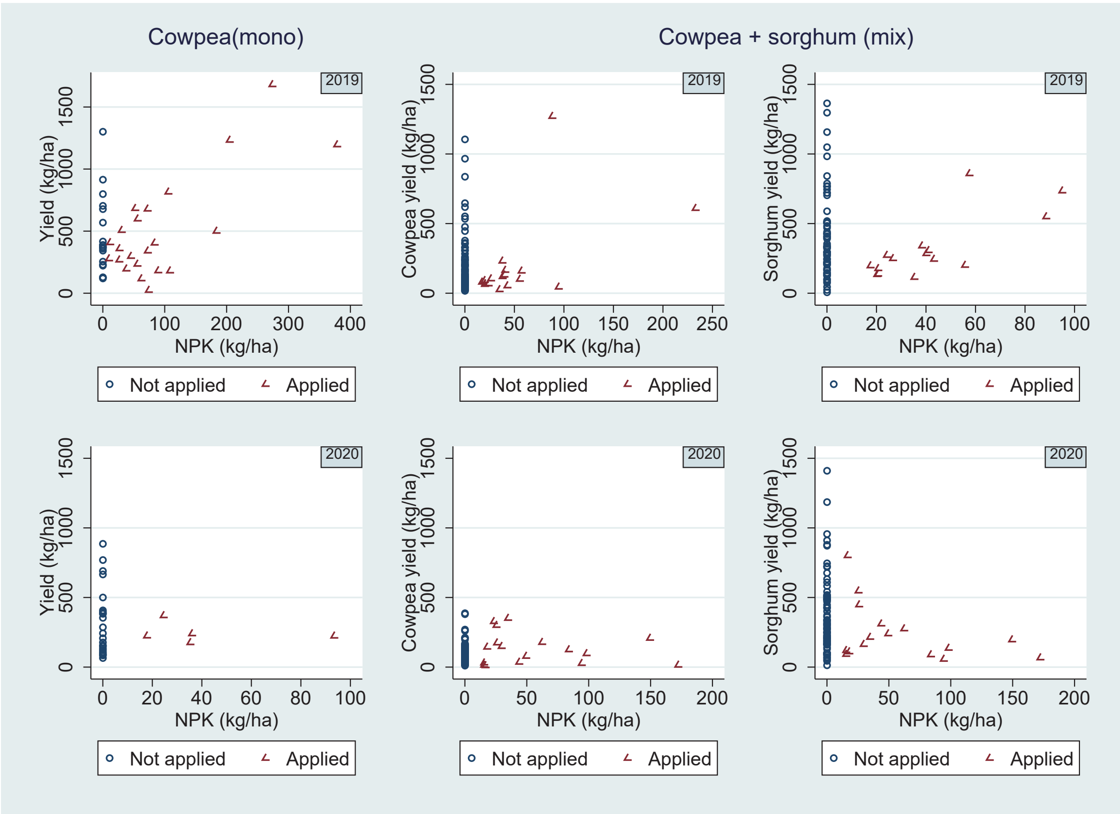

Figure 2. NPK application rates and yields of cowpea monocropping and mix cropping with sorghum in the 2019 cropping season (above) and the 2020 cropping season (below)

Due to the limited yield response to compound fertilizer and the associated acquisition costs, no significant differences were observed in the net income levels between fertilized and unfertilized fields (Figure 3). In cowpea monocropping and mixed cropping with sorghum, the average net income was slightly higher in non-fertilized fields than in fertilized ones. Furthermore, this lack of economic advantage in fertilized fields was observed not only in 2020, when rainfall was relatively scarce but also in 2019, when rainfall conditions were relatively favorable. As previously mentioned, a certain degree of yield response to fertilizer was observed in 2019; however, it was insufficient to offset fertilizer costs and generate income gains. Consequently, farmers' fertilizer application did not improve profitability regardless of rainfall conditions. This limited economic performance may have deterred farmers from expanding fertilizer use, compounded by financial constraints on its acquisition. In other words, the current behavior of farmers who do not overly rely on fertilizer application may be considered rational.

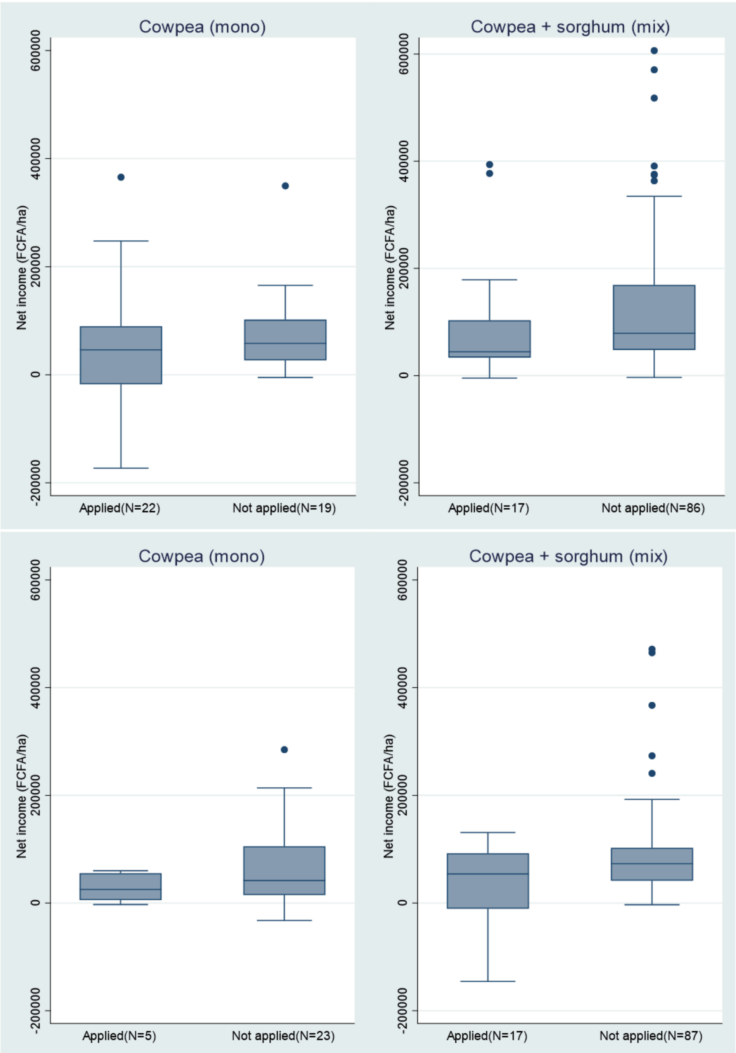

Figure 3. Net income of cowpea monocropping and mixed cropping with sorghum between NPK fertilized and non-fertilized fields in the 2019 cropping season (above) and the 2020 cropping season (below)

Net income: Gross income − Paid-out costs,

FCFA: Franc of the Communauté Financière Africaine (Currency)

To address the issue of the lack of economic advantage in fertilizer use, it would be informative to evaluate the extent to which reductions in fertilizer prices or increases in crop yields would be required to achieve this advantage. Therefore, we examined the fertilizer prices or yields at which the net income of fertilized plots significantly surpassed that of unfertilized plots (t-test, $p<0.05$). Unfortunately, even during the 2019 season, which exhibited relatively favorable fertilizer responses due to good rainfall, solely reducing fertilizer costs to zero (maintaining the observed yields) did not result in a significant difference; the average net income of fertilized plots—whether for cowpea monocropping or cowpea-sorghum mixed cropping—only slightly exceeded that of unfertilized plots. Under the current fertilizer pricing structure, a significant difference in net income between fertilized and unfertilized plots would only be observed if the yields of fertilized plots increased by approximately 93% for monocropping and 101% for mixed cropping. Even with a hypothetical subsidized fertilizer price, such as adopting half of the current price, a significant difference in net income would require the yields of fertilized plots to increase by 76% for monocropping and 93% for mixed cropping. Therefore, in addition to reducing fertilizer prices, innovative measures are necessary to substantially improve the profitability of fertilized production. These measures may include effective combinations of agronomic practices that complement fertilization and marketing strategies to enhance crop sale prices.

4. Concluding remarks

Consistent with previous studies documenting the suboptimal performance of fertilizer application in SSA, this study underscored the current inefficacy of compound NPK fertilizers in boosting farmers' economic returns. A substantial portion of the applied fertilizer was directed toward cowpea, a key cash crop in the study region, indicating farmers' attempts to maximize income from this high-value crop. However, the extent of NPK fertilizer application remained constrained, with application rates falling below the recommended levels. The reduction in application and application rates in 2020, a year characterized by relatively insufficient rainfall, implies that farmers adjusted their fertilizer usage in response to climatic conditions.

Our analysis indicates that although fertilizer application increased yields, particularly in 2019 when rainfall was adequate, these gains were insufficient to provide a substantial advantage over unfertilized production. In cowpea monocropping and mixed cropping with sorghum, the yield from fertilized plots was only marginally higher than that from unfertilized plots. Moreover, the average net income was slightly higher in unfertilized fields. This consistent lack of economic benefit from fertilizer application, observed in 2019 and 2020 despite varying rainfall conditions, likely dissuades farmers from expanding their use of fertilizers.

To address the economic shortcomings of current fertilizer use, it is essential to evaluate conditions that would render its application economically viable. Our analysis indicates that significant improvements in net income cannot be achieved solely by reducing fertilizer costs. Substantial economic benefits would require nearly doubling the crop yields for monocropping and mixed cropping under current price structures. Even with a hypothetical reduction in fertilizer prices to half the current level, realizing a significant economic advantage would require considerable yield increases. It is essential to determine the feasibility of such yield improvements through agronomic studies that examine the potential yields of fertilized crops.

Under current practices, merely increasing the application of fertilizers may not lead to improved crop yield or profitability; therefore, it is essential to advocate for appropriate agronomic practices that include the rational use of fertilizers. Practices that fully exploit the yield potential and significantly surpass the profitability of non-fertilized crops would be effective in incentivizing farmers to invest more in fertilizers and expand their usage.

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2-2 Economic viability of NPK fertilization using Burkina Faso phosphate rock on sorghum and cowpea

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Abstract

A promising agricultural technology to alleviate food insecurity and poverty among resource-constrained farmers in sub-Saharan Africa involves the strategic application of fertilizers derived from the region's abundant phosphorus resources. While the agronomic performance of this technology has been experimentally assessed with a promising outcome, its economic performance and superiority over low-cost, unfertilized production in actual farmers' fields have not been thoroughly investigated. Through participatory on-farm trials, this study illustrated the relative profitability of alternative NPK fertilization methods utilizing Burkina Faso phosphate rock for sorghum and cowpea production across various fertilizer price scenarios. Additionally, it evaluates the economic feasibility of expanding fertilized production using these alternative fertilization techniques among farmers. This analysis uses a whole-farm economic model based on linear programming, developed from comprehensive data across entire plots—including those using conventional and alternative fertilization methods—and designed to determine optimal combinations and adoption scales for these techniques. On-farm trial results indicate that alternative fertilization modestly improves yields for both sorghum and cowpea, with compound fertilizers containing partially acidulated phosphate rock and organic manure showing relatively high cost-effectiveness. Whole-farm economic analyses demonstrate that the optimal fertilized area using alternative fertilization techniques is similar to the current fertilized area when assuming approximately a 50% markup on the alternative fertilizer's production cost. This finding suggests that farmers are unlikely to gain economically from expanding fertilized production using alternative fertilizers if their prices exceed a 50% increase over base production costs. Therefore, reducing fertilizer manufacturing and transaction costs is essential to keep prices well below this threshold and/or to enhance yield effects through advancements in fertilization techniques and complementary agronomic practices.

1. Introduction

Soil nutrient depletion is a major biophysical factor contributing to the decline in per-capita food production in sub-Saharan Africa (SSA), posing a substantial threat to food security and economic development (Drechsel et al., 2001). Enhancing farmers' effective use of fertilizers is crucial to intensifying crop production and overcoming food insecurity (Sanchez, 2010; Jayne and Rashid, 2013; Holden, 2018). However, fertilizer use remains relatively low and inefficient in SSA compared to other regions of the world (Smale et al., 2011; Abate et al., 2020). Furthermore, access to affordable fertilizers is severely restricted for resource-constrained farmers in SSA. Most countries lack a domestic infrastructure for fertilizer manufacture, with landlocked nations facing fertilizer costs five to ten times as high as those in the Global North (Snapp et al., 2014). Recent disruptions caused by the COVID-19 pandemic and geopolitical conflicts have exacerbated the situation by severely disrupting global fertilizer supply chains, resulting in disproportionate price hikes and shortages in SSA (Njoroge et al., 2023). The limited effectiveness of fertilizers, coupled with rising acquisition costs, results in significantly low returns on investment for farmers, greatly reducing their incentives for fertilizer adoption and expansion. One effective strategy to overcome this challenge is developing more cost-effective fertilizer packages using locally available mineral resources, complemented by enhanced technical interventions to maximize their efficacy. Among these, phosphate rock fertilization holds promise in SSA (Margenot et al., 2016). Given that low soil phosphorous (P) is a major constraint on crop production in this region (Verde and Matusso, 2014), ready access to regionally adapted P fertilization techniques and appropriate guidance may significantly improve farmers' investment incentives and performance, potentially leading to broader fertilizer use.

In Burkina Faso, which is abundant in low-grade phosphate rock deposits, various P fertilization techniques have been proposed, including direct application of phosphate rock, application of calcinated phosphate rock (CPR) or partially acidulated phosphate rock (PAPR), and amendment with phosphate-rock-enriched composts. CPR and PAPR have been developed to increase the P solubility of low-grade phosphate rock and are expected to replace imported P fertilizers. The calcination process at 900 °C uses alkaline additives, resulting in high solubility in 2% citric acid (Nakamura et al., 2019). On the other hand, the acidulation of phosphate rock with sulfuric acid results in high water-soluble P and alkaline ammonium citrate-soluble P (Frederick and Roth, 1986). Different P solubility is a principal factor impacting the fertilization effect in upland crop cultivation in SSA (Iwasaki et al., 2022).

The agronomic effects of these P fertilization techniques have been experimentally evaluated with promising results (Iwasaki et al., 2022; Nakamura et al., 2019; Nakamura et al., 2020; Sagnon et al., 2022). However, their economic viability has not been adequately verified in actual farming. It is imperative to carefully assess whether the promoted P fertilization techniques enable farmers to achieve satisfactory outcomes, potentially through well-designed on-farm experiments. On-farm experimentation has gained renewed prominence in agricultural sciences globally (Lacoste et al., 2021). However, inappropriate design choices may compromise its validation. In fertilizer trials, researchers highlight a critical gap in fertilizer use efficiency between researcher- and farmer-managed fields, attributed to differences in agronomic management, soil resource endowments, and non-random participant selection in most on-farm experiments (Snapp et al., 2014; Tittonell, 2008). Addressing these experimental design issues is critical in validating proposed fertilization techniques in farmers' fields.

Beyond on-farm agronomic experimentation, whole-farm economic evaluation is necessary to thoroughly analyze the viability of farmers' adoption of fertilization techniques and to recommend optimal application strategies. Existing economic assessments of fertilizer use in SSA primarily focus on determining cost-effective application rates for specific crops (e.g., Ouattara et al., 2017; Rurinda et al., 2020) or assessing the crop-specific profitability impact (e.g., Burke et al., 2019; Dabessa Iticha et al., 2021; Kiwia et al., 2022). However, these analyses may inadequately assess whether recommended fertilizer use is beneficial for farmers at the whole-farm level, as optimizing resource use for specific crops could inadvertently compromise resource use for other crops. This suggests that recommended fertilizer applications may not necessarily benefit the overall farm's economic performance, potentially resulting in neutral or adverse effects. The concern is particularly relevant but often overlooked in smallholder production systems in SSA, where limited resources are allocated across diversified crop enterprises to mitigate risks and ensure multiple food and income sources. Therefore, economic analyses addressing tradeoffs in efficiently allocating scarce resources among competing demands are crucial to support smallholder production systems (Williams et al., 2019).

This study examines the profitability of different fertilization techniques utilizing Burkina Faso phosphate rock (BPR) based on participatory on-farm trials and surveys conducted in central Burkina Faso during the 2021 rainy season. Furthermore, the study evaluates the economic viability of scaling up these techniques across farmers' fields.

2. Materials and methods

2.1 On-farm trials

The trial participants consisted of 20 randomly selected smallholder farmers in the Boulkiemde province, Centre-Ouest region of Burkina Faso. These farmers all practice mixed cropping of sorghum and cowpea, the region's primary food and cash crops. Appropriate use of BPR on sorghum and cowpea has been found to increase P use efficiency and grain yield (Iwasaki et al. 2022). Therefore, the on-farm trials focused on the fertilization of these two crops. NPK compound fertilizers were primarily treated as they are the most commonly available in smallholder farmer communities across SSA (Roobroeck et al. 2021), and the study site is no exception. The trial plots were selected based on soil conditions from portions of the participants' sorghum- and cowpea-cultivated fields. The fertilizer application techniques experimented with in the trial combined BPR-derived compound fertilizers (using different P fertilization methods) with the appropriate sowing intervals, amounts, and timing of fertilizer application. The trial also covered conventional practices, including no-fertilizer application (as a negative control) and organic manure application. Specific treatments include: T1) no fertilization (-N-P-K), T2) compound fertilizer application utilizing CPR (+N+P+K), T3) compound fertilizer application utilizing PAPR (+N+P+K), T4) compound fertilizer application utilizing CPR (+N+P+K) and manure, and T5) compound fertilizer application utilizing PAPR (+N+P+K) and manure. Compound fertilizers were applied at 37 kg N ha^{-1}, 45 kg P_2O_5 ha^{-1}, and 14 kg K_2O ha^{-1}. The plot size for each treatment was 50 m^2 (5 m × 10 m).

2.2 Surveys

We comprehensively surveyed sorghum and cowpea grain yields across all on-farm trial plots for each treatment. Similarly, we visited all other plots cultivated by trial farmers without omission (n=237), directly measuring each plot's size and the harvest quantity of each crop for yield evaluation. Additionally, to gather accurate data on field crop management in both trial and non-trial plots, we provided each farmer with scales and recording materials, along with detailed instructions on their use, to measure and record daily amounts and costs of inputs (seeds, fertilizer, herbicide, and insecticide) and the number of persons, hours, and wages paid for each crop production. Our field staff regularly monitored and assisted in the measurement and recording activities and cross-checked the data before we double-checked it for approval. This data collection and inspection method was adopted to mitigate farmers' recall and measurement errors inherent in agricultural questionnaires and significantly undermine the reliability of agricultural output, input, and productivity variables (Wollburg et al., 2021).

2.3 Analysis

We evaluated the relative profitability of sorghum and cowpea mixed cropping across different treatments. Due to the unavailability of compound fertilizers derived from CRR and PAPR in the market, we established several price scenarios: Scenario 1 represents the baseline production cost of the alternative fertilizer, while Scenarios 2 and 3 represent prices with a 50% and 100% markup on this baseline, respectively. The base production cost was estimated by the fertilizer developers. Additionally, we conducted a whole-farm economic analysis to evaluate the economic viability of expanding alternative fertilization techniques across farmers' fields. The applied analytical model was developed individually for each household and formulated through single-objective linear programming, simultaneously optimizing the allocation of multiple farm resources to maximize system-wide profitability while securing household food security. This model is an application of the African Smallholder Farm Management Model (ASFAM), described in Chapter 1-2.

To identify the optimal choices and adoption scale of alternative NPK fertilization techniques, the cropping options used in the model encompassed not only the conventional cropping systems practiced by each household outside on-farm trials, including both fertilized and non-fertilized crops but also the trial-based cropping systems utilizing new compound fertilizers (i.e., T2, T3, T4, and T5). Since all trial participants were smallholder family farms pursuing income, the model was designed to maximize the total income as the objective function. All parameters for each cropping option, including yield, labor hours, costs, and sale prices, were based on observed values. However, the net income from the trial-based cropping systems was analyzed across varying fertilizer price scenarios. This approach aims to conduct a sensitivity analysis to estimate the price (markup over the base production cost) of the new fertilizer required to achieve an optimal fertilized area comparable to current fertilization levels. The estimated price can be interpreted as the minimum target to be achieved for expanding fertilized crop production using alternative fertilizers. The farm resources considered in the model include available farmland, categorized into upland crops, lowland rice, and vegetable plots, as well as available labor, accounting for the seasonality of both family and hired labor inputs as documented in daily farm operation records. The model was designed to ensure that each household secures sufficient acreage to meet annual consumption requirements for all crops produced based on current yields.

3. Results

3.1 On-farm trials

In the treatments using alternative NPK fertilizers (T2, T3, T4, and T5), grain yields were higher than for unfertilized treatments (T1), as shown in Table 1. However, multiple comparisons revealed no statistically significant differences among the treatments (Tukey, $p<0.05$), likely due to the generally low yields across all treatments and the limited sample size. The net incomes of T2 and T3 were lower than those of T1, even under the production cost-based fertilizer price Scenario 1, primarily due to the higher costs of alternative fertilizers. Notably, net income from CPR-based compound fertilizer usage was negative under price Scenarios 2 and 3. Due to the relatively high yields and low organic manure costs, net income from the combined uses of alternative NPK fertilizers and organic manure (T4, T5) was improved over NPK fertilizers alone. Nonetheless, net income from CPR-based compound fertilizer combined with organic manure (T4) was substantially lower than that with no fertilization (T1), even under fertilizer price Scenario 1. Conversely, net income from PAPR-based compound fertilizer combined with organic manure (T5) slightly exceeded the no-fertilizer case under the same price scenario. Therefore, based on trial results, the combination of PAPR-based compound fertilizer and organic manure appears relatively cost-effective. However, determining whether adopting and expanding alternative fertilization technologies is recommended for farmers requires whole-farm economic analyses.

Table 1. Summary of the on-farm trial results

	T1	T2	T3	T4	T5
Sorghum yield (avg. kg/ha)	156	203	212	305	339
Cowpea yield (avg. kg/ha)	382	458	515	684	638
Net income (avg. FCFA/ha)					
Price Scenario 1	159,155	8,703	118,933	108,031	169,380
Price Scenario 2	159,155	-89,147	60,747	10,181	111,195
Price Scenario 3	159,155	-186,998	2,562	-87,669	53,010

T1: No fertilization (-N-P-K), T2: NPK (CPR), T3: NPK (PAPR), T4: NPK (CPR) +Manure, T5: NPK (PAPR) +Manure, Net income: Gross income − Paid-out costs, FCFA: Franc of the Communauté Financière Africaine (1 FCFA= 0.016 USD as of October 30, 2024)
The price scenarios of the alternative fertilizer determine the net incomes for T2, T3, T4, and T5. Price Scenario 1 reflects the base production cost of the alternative fertilizer, whereas Scenarios 2 and 3 represent prices with a 50% and 100% markup on the production cost, respectively.

3.2 Whole-farm economic evaluation

Most farmers' crop fields are occupied by production without fertilizer, with the share of the production with conventional fertilizer being only 7%. Based on the linear programming model described above, sensitivity analysis indicated that the price of the alternative NPK fertilizer requires an optimal fertilized area comparable to current levels with approximately a 50% markup over its production cost (Table 2). This finding suggests that expanding fertilized crop production through alternative fertilization methods would not be economically feasible unless the price markup is kept below 50%. Under this fertilizer price scenario, the economically optimized adoption scale of fertilized crop production consists of 4.3% sorghum and cowpea production using alternative fertilizers and 2.2% of other crops with conventional fertilizers.

Although not indicated in Table 2, the number of farmers adopting new sorghum and cowpea cropping systems using alternative NPK fertilizers represents only about one-fourth under a 50% markup. The optimal choices of alternative NPK fertilizers (and their adoption scales) vary among farmers, consisting of PAPR-based fertilizers and CPR-based and PAPR-based fertilizers combined with organic manure.

When the markup on the production cost of the alternative fertilizer exceeds 50%, the optimal adoption scales of new cropping systems diminish, encompassing only those utilizing PAPR-based fertilizer (combined with organic manure). This reduced fertilized area is subsequently replaced by an unfertilized production area. The primary reason for this is the lower profitability of crop production using alternative fertilizers compared to conventional, low-cost, unfertilized crop production. In sorghum and cowpea mixed production, the net incomes of alternative fertilization techniques in trial fields do not significantly exceed those of conventional unfertilized techniques in non-trial fields. Therefore, most crop production without fertilizer application, predominantly sorghum and cowpea mixed cropping, has not transitioned to production with alternative fertilizers in the optimal solution.

Table 2. Share of the optimal adoption area for various fertilization cropping systems to the total farmland area (as determined by the linear programming model under a 50% markup to the production cost)

	Share (%)
Sorghum + cowpea mixed cropping (+N+P+K: CPR)	0
Sorghum + cowpea mixed cropping (+N+P+K: PAPR)	3.8
Sorghum + cowpea mixed cropping (+N+P+K: CPR with manure)	0
Sorghum + cowpea mixed cropping (+N+P+K: PAPR with manure)	0.5
Other cropping systems with conventional fertilizer application	2.2
Total	6.5

4. Conclusion

Through participatory on-farm trials and surveys, this paper highlights the profitability of alternative BPR-based NPK fertilization techniques for sorghum and cowpea production under various fertilizer price scenarios. Furthermore, it estimates the impact of these techniques on expanding fertilized crop production among farmers. On-farm trial results underscore that alternative fertilization techniques slightly enhance yields for both sorghum and cowpea, particularly the combined application of PAPR-derived compound fertilizers and organic manure, which show relatively high cost-effectiveness. Whole-farm economic analyses demonstrate that the optimal fertilized area using alternative fertilization techniques is similar to the current fertilized area when assuming approximately a 50% markup on the alternative fertilizer's production cost. This finding suggests that farmers are unlikely to gain economically from expanding fertilized production using alternative fertilizers if their prices exceed a 50% increase over base production costs. Therefore, reducing fertilizer manufacturing and transaction costs is essential to keep prices well below this threshold and/or to enhance yield effects through advancements in fertilization techniques and complementary agronomic practices. If these efforts yield positive results and demonstrate to farmers superior economic advantages over the prevailing unfertilized cropping systems at the whole-farm level, it could potentially stimulate broader adoption of fertilized production.

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Chapter 3 Issues and model-based optimization of smallholder technology adoption in lowland cropping systems: Case of irrigation technology in northern Ghana

3-1 Challenges and opportunities of utilizing small reservoirs for rice irrigation in northern Ghana

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Abstract
Rainwater-harvesting reservoirs in Africa offer substantial potential to support rice irrigation and boost productivity in rainfed lowland areas. However, the effectiveness of such irrigation initiatives hinges on multiple factors beyond hydrological conditions, including social regulations governing irrigation and facility maintenance, availability of labor and financial resources, farmers' willingness to engage in rice irrigation, and economic viability, which have been underrepresented in the literature. This chapter seeks to address these knowledge gaps and examine the challenges and opportunities of rice irrigation using small reservoirs in northern Ghana, drawing upon field survey findings by Koide et al. (2015) and Yokoyama and Koide (2018). These findings highlight the importance of restricting rice irrigation to supplementary practices during the rainy season, considering that local reservoirs experience reduced water levels during the dry season, prioritizing domestic water supply. Key challenges to the implementation of supplementary irrigation include the absence of customary rules that regulate water use to enable timely irrigation and the competition for labor and financial resources between intensified rice farming and the cultivation of upland crops. There is also a lack of institutional mechanisms to address these farm resource constraints. Based on an analysis of local major crop production costs and on-farm trials of supplementary rice irrigation, the authors further demonstrated that rice yields under supplementary irrigation are increased to a level that exceeds the profitability of pepper, the region's most lucrative crop. These findings suggest that supplementary irrigation can enhance rice productivity and support its expansion as a cash crop, potentially replacing other high-value crops.

1. Introduction

The increasing variability in rainfall patterns and excessive non-productive water losses in smallholder agricultural systems across Africa underscores the urgent need for widespread rainwater harvesting and supplementary irrigation techniques to improve water-use efficiency and long-term sustainability (Biazin et al., 2012). Crops with the greatest demand for these techniques include rice, which is highly vulnerable to water stress. Its production persistently falls short of consumption, a disparity further aggravated by urbanization and shifting dietary preferences across the continent

(Zenna et al., 2017). In rainfed lowland environments, which are a key rice-growing area in West Africa, productivity declines and variability due to intra-seasonal dry spells pose critical challenges, emphasizing the importance of appropriate water management and complementary agronomic practices to support the sustainable intensification and expansion of rice production (Katic et al., 2013).

In particular, Ghana, where rainfed lowlands represent nearly 80% of the rice cultivation area (Seck et al., 2010) and small reservoirs are abundant (Namara et al., 2010), offers a significant opportunity for efficient, stable irrigation operations utilizing existing water infrastructure to enhance rice yields in rainfed lowlands. However, the success of such operations depends on several factors beyond hydrological conditions, including social regulations governing irrigation and facility maintenance, the availability of labor and financial resources, farmers' interest in irrigated farming, and its economic viability compared to rainfed agriculture.

Research on these socioeconomic dimensions remains limited. For example, Venot et al. (2011) explored the roles and decision-making processes of stakeholders managing small reservoirs in northeastern Ghana, including local water user associations, traditional authorities, and government officials. Similarly, de Fraiture et al. (2013) examined water-use trends for small reservoirs in central Burkina Faso, identifying unsustainable practices such as the unregulated expansion of irrigated areas using motorized pumps. However, these studies primarily focused on large reservoirs, often beyond the management capacity of farmers, and did not sufficiently address the opportunities and challenges of water use for rice cultivation. Additionally, few studies have investigated the profitability of irrigated rice or its potential tradeoffs with the production of other crops. This chapter examines the potential for rice irrigation and expansion using small reservoirs in northern Ghana, drawing on field survey findings by Koide et al. (2015) and Yokoyama and Koide (2018) to address this lack of knowledge.

2. Field surveys

Koide et al. (2015) conducted preliminary surveys in 2013 in three villages (Village N, Village S, and Village D) in the former Northern Region of Ghana, the region with the highest rice production. These sites were selected due to the presence of small communal rainwater harvesting reservoirs, known as dugouts, which are surrounded by rainfed rice fields, thus presenting the potential for reservoir-based rice irrigation. Focus group discussion with village representatives, including traditional chiefs, was conducted to gather information on the current uses of the reservoirs, customary rules regarding water access and facility maintenance, and other social dimensions. Additionally, a semi-structured questionnaire survey with 15 randomly selected rice-producing households was carried out to understand the demand for rice irrigation and key requirements for its adoption, such as labor availability and financial resources. The survey results highlight the multidimensional constraints on rice irrigation, as described in Section 3, Potential for rice irrigation.

Building on the results of these preliminary surveys and parallel hydrological assessments, a more detailed survey was conducted between 2014 and 2015 in Village N, which was deemed more suitable for small-reservoir-based rice irrigation (Yokoyama and Koide, 2018). This survey targeted all rice-producing households (151 in 2014 and 167 in 2015) in Village N and two surrounding villages. A structured questionnaire was administered to collect data on production costs, yields, and sale prices of the major crops grown in the villages, including rainfed rice, maize, and pepper, as well as irrigated rice, which was experimentally grown using reservoir water under the technical guidance of the Japan International Research Center for Agricultural Sciences (JIRCAS). The collected data served to evaluate the relative profitability of these crops. The findings highlight the potential for rice expansion, including the substitutability of other crops for rice, as described in Section 4, Potential for rice expansion.

3. Potential for rice irrigation

3.1 Consistency with customary water uses and regulations

None of the surveyed villages have access to rivers or springs that provide year-round water, so water for domestic use—such as drinking, cooking, washing, and brick-making—as well as water for livestock, is mainly sourced from dugouts. These dugouts were constructed with government assistance and are used by most villagers. While wells exist in Villages N and S to secure water for domestic use, they dry up during the dry season or become murky, leading to limited use. Some residential areas in the villages have access to piped water at a cost, but this is used by only a small portion of the population. Therefore, for most villagers, dugouts represent the only source of domestic water supply throughout the year. However, the dugouts nearly dry up by the end of the dry season, making it difficult to use the water for dry-season irrigation (Koide et al., 2015).

All villages have implemented regulations to manage the quantity and quality of reserved water (Table 1). Since livestock intrusion degrades water quality, and water for livestock competes with domestic water requirements during the dry season, Villages N and D have established rules mandating that cattle be taken to alternative water sources, such as large dams in neighboring villages. In Village S, farming near the dugout is prohibited to prevent sedimentation. Maintenance of the dugouts, such as repairing embankments or dredging, involves the participation of all villagers. These rules, however, are not formalized, and there are no water user associations to oversee dugout use. Nevertheless, each village selects a few individuals to monitor the dugout and enforce the rules. Typically, the village chief organizes maintenance activities based on reports from these monitors. Violations of the rules are subject to penalties imposed by the chief (Koide et al., 2015).

Despite these regulations, there are no restrictions on water withdrawal to avoid future shortages. Villagers continue to use dugout water until it runs out, then move to neighboring villages' reservoirs to collect water. This practice complicates the storage of water surplus for irrigation but facilitates dredging activities. In Villages S and D, villagers gather at the end of the dry season, when reservoir levels are at their lowest, to dredge the dugouts and repair or raise the embankments. Neglecting these maintenance activities may significantly decrease the reservoir’s storage capacity, undermining its ability to ensure a dependable water supply for both domestic and irrigation purposes. Consequently, storing water for rice cultivation during the dry season is impractical due to the challenges associated with maintenance. Effective rice irrigation will likely be confined to supplementary measures during the rainy season when reservoir water levels are substantially higher (Koide et al., 2015).

Table 1. Major enforced rules for the use of village dugouts

	Village N	Village S	Village D
Prevent cattle from drinking reservoir water in the dry season	✓		✓
Refrain from walking and swimming	✓	✓	✓
Refrain from irrigating during the dry season	✓		
No cultivation near the reservoir		✓	✓
Participation in reservoir maintenance	✓	✓	✓

Source: Koide et al. (2015)

3.2 Availability of farm resources required for irrigation farming

The households surveyed throughout villages primarily cultivate upland crops, livestock, and rice (Table 2). Farmers in Village D, characterized by abundant uncultivated land, possess larger landholdings than those in the other two villages. Conversely, farmers in Village N, where minimal uncultivated land remains, have less than half the land of those in Village D despite having a similar number of household members. While many residents in Village D practice shifting cultivation, farmers in Villages N and S frequently rotate crops in upland areas to mitigate soil fertility decline. In lowland areas, where crop rotation poses more significant challenges, many residents engage in rainfed rice cultivation supplemented with chemical fertilizers (Koide et al., 2015).

Introducing irrigation and other agronomic practices in these rainfed lowlands may greatly enhance rice yields, but this poses challenges in securing adequate labor. For instance, the efficient utilization of irrigation water necessitates land leveling, a practice that is currently infrequent yet critical. Similar to plowing, manual land leveling is labor-intensive and coincides with the sowing season (May–June) for key upland crops such as maize, resulting in seasonal labor shortages. To mitigate this issue, employing tractors or draft animals for plowing and leveling is vital; however, the number of farmers possessing tractors or draft animals is limited in all villages. Furthermore, securing funds to rent tractors and procure chemical fertilizers is crucial for irrigated rice cultivation, yet some farmers are already allowing land to lie fallow due to insufficient resources. Thus, introducing irrigation may exacerbate competing labor and financial demands between rice and upland crop farming (Koide et al., 2015).

Currently, farmers in all villages cultivate maize, pepper, yam, cassava, groundnuts, and soybeans in addition to rice, reflecting a widespread diversification of crop farming. Among these, maize and cassava are prioritized for household consumption, while rice is primarily grown as a cash crop, with many farmers selling more than half of their rice harvest. Cassava, yam, pepper, and groundnuts are planted in May, and the peak farming season commences in June and July when rice, maize, and soybeans are sown. Most farmers prioritize the production of staple food crops while diversifying their agricultural endeavors, and considering that rice planting occurs during the peak labor season, it is challenging for farmers to allocate labor and financial resources to irrigate rice without compromising those needed for upland crop farming. Moreover, the fields of groundnuts, maize, and soybeans, which represent significant cash crops for the villagers, are often plowed by tractors, similar to rice fields, thereby intensifying competition for cropping activities. Therefore, the profitability of rice cultivation becomes crucial for farmers seeking to allocate labor and financial resources toward rice production. Some farmers opt to sell rice in early spring when prices peak, enabling them to afford tractor services for the subsequent cropping season. This strategy not only enhances rice profitability but also aids in avoiding fallow periods by ensuring access to tractor services (Koide et al., 2015).

Table 2. Surveyed households' labor, land, and livestock holdings

	Village N	Village S	Village D
Avg. number of household members	16.8	10.0	17.6
Avg. number of farm laborers	7.2	5.2	6.4
Avg. size of farmland holdings (ha)	4.8	5.3	9.9
- Upland crops (ha)	2.9	2.4	5.4
- Lowland rice (ha)	0.8	1.2	1.9
- Vegetables (ha)	0.5	0.5	1.1
- Fallow (ha)	0.4	0.5	1.0
- Uncultivated land (ha)	0.2	0.7	0.5
Avg. number of cattle	5.5	2.0	8.0
Avg. number of medium livestock	7.3	12.6	25.8
Avg. number of small livestock	82.8	67.0	73.8

Note: Medium livestock includes goats and sheep. Small livestock includes chickens, guinea fowl, and rabbits.

Source: Koide et al. (2015)

3.3 Availability of institutional mechanisms to mitigate resource constraints

Agricultural funding and securing domestic water resources might be addressed through institutional mechanisms. Some farmers obtain agricultural financing by borrowing from acquaintances or merchants, while others acquire inputs like chemical fertilizers on credit, repaying them post-harvest. However, many still face substantial financial challenges that hinder their ability to maintain continuous cultivation. Moreover, access to formal financial institutions such as banks remains limited. While water supply systems could help secure domestic water, no examples exist of villagers taking loans for this purpose. These challenges highlight the critical need for broader financial services to support agricultural financing and domestic water access (Koide et al., 2015).

Organized efforts may also address these issues. According to the principal activities of farmer organizations (Table 3), some groups (B, D, F) in Villages N and S store harvested crops, such as rice, collectively, selling them during the off-season to fund tractor use, chemical fertilizers, and new water supply systems. However, these organizations are relatively new and may encounter operational difficulties similar to those of older, now inactive, farmers' groups. For example, in Village N, an organization initially formed to secure tractors and chemical fertilizers, gradually faced financial constraints, rendering it nearly inactive. Another organization in the same village, created under an agricultural development project to provide chemical fertilizers and technical support, dissolved once the project ended. Thus, addressing agricultural funding and domestic water issues through collective action will require a reassessment of fund management and stronger institutional support (Koide et al., 2015).

Table 3. Main activities of organizations in which the surveyed farmers participate

	Organization (members)	Main Activities
Village N	A (40)	Mutual assistance in agricultural work
	B (42)	Labor exchange in weeding, joint storage, and sale of maize and rice
Village S	C (16)	Joint cultivation and sale of rice
	D (65)	Joint cultivation and sale of maize and rice
	E (30)	Labor exchange in rice sowing
	F (52)	Joint marketing of maize and soybeans
Village D	G (30)	Mutual assistance in agricultural work, weddings, funerals

Source: Koide et al. (2015)

3.4 Farmers' perceptions of rice production

It is also important to note that rice irrigation may not necessarily align with farmers' perceived solutions to the practical challenges they face in rice production. Notably, farmers in all villages emphasize soil and weed issues as major factors hindering rice production (Table 4). Their awareness of water shortages is limited, particularly in Village D, where farmers observe adequate soil moisture in paddy fields due to frequent flooding. Given that rice yields in this village are lower than the other two, water scarcity may not be the primary contributing factor. Many farmers attribute annual fluctuations in rice yields to soil and weed management issues, such as the lack of funds to purchase chemical fertilizers and herbicides. However, in Villages N and S, many farmers point to rainfall instability as a concern. Farmers in Village S reported that flooding after sowing washed away seeds, resulting in reduced yields. Although farmers in Village D have not faced water shortages, they note that delays in sowing can lead to water deficits before heading. The impact of flood timing and the onset of rainfall on yield fluctuations highlight the importance of timely sowing and supplementary irrigation (Koide et al., 2015).

Table 4. Farmers' perceptions of rice production constraints and yield fluctuations

	Village N	Village S	Village D
Yield (Avg. t/ha)	3.06	1.54	1.06
Production constraints (0–5 points)			
- Water shortage	2.6	2.6	0
- Soil infertility	4.1	2.8	4
- Weed problem	3.8	5	4.8
- Pests and diseases	0.6	0.6	0
- Bird attack	2.2	1.4	2.8
Causes of yield fluctuation (person)			
- Rainfall instability	4 (80%)	5 (100%)	1 (20%)
- Lack of fertilizers	4 (80%)	2 (40%)	5 (100%)
- Lack of herbicides	2 (40%)	3 (60%)	5 (100%)

Note: Production constraints were rated from 0 for "no problem at all" to 5 for "very problematic."
Source: Koide et al. (2015)

4. Potential for rice expansion

4.1 Profitability of rice and other crops

A household census conducted in 2014 in Village N and two neighboring villages revealed that the primary crops in these three villages are maize (46% of the total cultivated area), rice (20%), and pepper (18%), collectively accounting for 84% of the total cultivated area. The primary cultivation purposes were self-consumption for maize, sales for pepper, and a mix of both for rice. The average cultivated area was 0.5 hectares for maize and rice and 0.3 hectares for pepper, with yields ranging from 1 to 3 tons per hectare for all three crops. The yield and price of rice and maize were relatively stable, while pepper, a high-market crop, exhibited significant fluctuations. Between 2014 and 2015, pepper yields halved, while prices doubled, as shown in Table 5 (Yokoyama and Koide, 2018).

Regarding production costs, labor accounted for the largest share across all three crops, with rice ranging from 50–60%, maize at 40%, and pepper as high as 90%. The reliance on hired labor was particularly pronounced for rice, reaching 37% in 2014 and 23% in 2015. Rice is harvested by cutting the stalks with a sickle, piling them in the field, threshing by beating with sticks, and winnowing using large bowls—a series of tasks often performed by groups of hired women. Consequently, there is a parallel relationship between rice yields and female employment. A 22% decrease in rice yields from 2014 to 2015 corresponded to a 27% reduction in employment. Thus, increasing rice production contributes to expanding local employment opportunities for women. Moreover, payment for threshing and winnowing is often made in paddy rather than cash, which is expected to directly improve food security for poorer households (Yokoyama and Koide, 2018).

In terms of income and profit, pepper demonstrated significantly higher profitability with its high sales price and labor-intensive nature. The expansion of pepper production is expected to substantially contribute to regional economic development. However, the potential for a price collapse due to overproduction in neighboring villages must be considered. Furthermore, pepper seedlings require frequent irrigation, currently sourced from dugouts or water systems, limiting seedling production to areas near residences. After transplanting them to the main field, considerable family labor is required for management and harvest, with water resources and labor availability being key constraints to expansion (Yokoyama and Koide, 2018).

Table 5. Profitability of the major crops (GHS/ha, 2014 and 2015 cropping seasons)

	2014 cropping season			2015 cropping season			
	Rainfed rice (n=141)	Maize (n=75)	Pepper (n=75)	Rainfed rice (n=167)	Irrigated rice [1] (n=10)	Maize (n=125)	Pepper (n=42)
Cultivated area (Avg. ha/plot)	0.45	0.61	0.33	0.49	0.125	0.56	0.33
Yield (t/ha)	2.04	1.52	2.45	1.60	4.06	1.86	1.19
Sale price (GHS/kg)	1.07	0.84	3.04	1.09	1.085	0.92	6.30
Gross income (GHS/ha) (A)[2]	2,186	1,277	6,184	1,732	4,403	1,705	6,781
Production cost (B)	2,172	1,121	5,590	1,672	5,802	1,053	4,462
- Material	604	564	611	660	785	495	539
- Family labor (C)[3]	886	395	4389	648	4,423	362	3,790
- Hired labor	526	76	554	200	182	55	83
- Custom hiring	157	86	36	164	125	142	50
- Irrigation fee	0	0	0	0	216	0	0
Income A–B+C	899	550	4,983	708	3,025	1,014	6,109
Profit A–B	14	155	594	61	-1,398	652	2,319

Notes:

1) In the experimental field established by JIRCAS, ten farmers selected from the village followed the instructions of staff from the Ghanaian experimental station regarding fertilization and crop management.

2) The average gross income was calculated individually and may not correspond exactly to the product of average yield and average sales price.

3) Labor costs were estimated as the number of labor days multiplied by the average agricultural wage rate (3.3 GHS/day in 2014 and 3.4 GHS/day in 2015). No significant differences in wage levels were observed by task or gender. In actual farm operations, no payment is made for family labor, so family labor costs are considered imputed. These were accounted for as they are necessary for calculating farm profits.

Source: Modified from Yokoyama and Koide (2018)

4.2 Substitutability of other crops for rice

While it has been established that pepper is the most profitable crop in the surveyed villages, it is important to determine the level of rice yield necessary for its profitability to match that of pepper, assuming current technologies. The following equation is obtained by performing a linear regression of per-hectare profit with rice yield.

2014 cropping season: Y = 615.17 X − 1,235 (n = 141, r^2 = 0.3667)

2015 cropping season: Y = 757.29 X − 1,145 (n = 167, r^2 = 0.4889)

Y: Profit (GHS/ha), X: Rice yield (t/ha)

From the above equation, estimating the rice yield required to achieve the average profitability of pepper (GHS 594/ha in 2014 and GHS 2,319/ha in 2015) shows that 3.0 t/ha in 2014 and 4.6 t/ha in 2015 would be necessary. The 1.5-fold difference between these years is primarily attributed to the price fluctuations of pepper, which increased by 2.1 times between 2014 and 2015 (Yokoyama and Koide, 2018).

In the supplementary irrigation trials for rice conducted by JIRCAS in Village N, yields of 4.1 t/ha (2015) and 4.7 t/ha (2016) were obtained in farmer-managed fields. Achieving these yield levels would make rice profitability comparable to the average profitability of pepper, indicating the potential for a partial shift from pepper to rice cultivation. Additionally, as rice becomes more favored as a staple food, a shift from maize to rice is also conceivable. In fact, fields located between the settlement and wetland areas already exhibit flexible cultivation of rice, maize, and pepper, depending on conditions such as rainfall. No new land development or irrigation channel construction is required in such locations, making it possible to convert to rice cultivation with only basic field preparation (Yokoyama and Koide, 2018).

However, additional labor is required when irrigated rice is cultivated in newly developed paddy fields, including repeated land preparation (which involves plowing and leveling), replanting, weeding, and irrigation labor. Although this additional labor was provided by family members during the trials, leading to incomes significantly exceeding those of current rainfed rice cultivation due to increased yields, the profits, when accounting for the imputed cost of family labor, showed a substantial deficit (Table 5). Since the additional labor associated with new paddy field development is part of the cost of introducing irrigated rice, it seems appropriate for farmers to bear this burden. However, it is expected to decrease as continuous rice cultivation stabilizes the field conditions (Yokoyama and Koide, 2018).

5. Concluding remarks

Small-scale irrigation leveraging existing local water infrastructure, such as rainwater-harvesting reservoirs, presents a viable strategy for enhancing rice production in Ghana. However, findings from Koide et al. (2015) emphasize that the current applications of these reservoirs are varied and not conducive to prioritizing rice production. Specifically, utilizing reservoir water for rice during the dry season presents challenges, as the need for domestic water supply takes precedence, resulting in inadequate water storage and complicating implementation. It appears prudent to restrict irrigation to supplementary practices during the rainy season. In such instances, it is vital to establish a framework for water allocation and the maintenance of reservoirs, necessitating enforcement of irrigation regulations and cooperation. Additionally, strategic farm management and institutional arrangements are essential to ensure the timely provision of labor and funding for land development and fertilization, which are critical to guaranteeing effective irrigation and its associated benefits. By satisfying these diverse conditions, supplementary irrigation farming utilizing small reservoirs could become feasible, enabling rice intensification and expansion. As demonstrated by Yokoyama and Koide (2018), while current rainfed rice production is significantly less profitable than pepper, a major cash crop, adopting supplementary irrigation and complementary agronomic practices could yield sufficient increases in rice yield, surpassing pepper's profitability. Alternatively, farmers could substantially increase their incomes by expanding rice cultivation in lieu of other competing, less profitable crops. However, rice expansion must be carefully balanced to avoid undermining farmers' risk management strategies, such as producing other food staples like maize and diversifying income sources.

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3-2 Optimal implementation strategies of rice and vegetable irrigation using small reservoirs in northern Ghana

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Abstract

Small-scale irrigation using rainwater-harvesting reservoirs is effective in enhancing the adaptation of predominantly rainfed and vulnerable production systems to climate change in African drylands. However, the required technological improvement, participatory breakthroughs, farm risk management, and investment justification are rarely established comprehensively and integrated into adaptive planning. This chapter highlights the outputs from Koide et al. (2021), which explored reservoir-based irrigation cropping strategies synthesizing technological, participatory, managerial, and investment capabilities. They crafted an innovative rice and vegetable pond irrigation system as a technological contribution. The system was validated through a five-year participatory on-farm experiment in northern Ghana. Using agronomic, hydrological, and socioeconomic data obtained from the experiments and surveys, they constructed bioeconomic models to identify optimal irrigation cropping strategies that are the most efficient in securing smallholders' food and income and resilient to interannual climate fluctuations. The net present values were computed to determine the financial effects of the identified strategies on the investment payback of the pond system. The on-farm experiment results indicate that supplementary irrigation increased the average rice yield by 23%, more than doubled the profitability, and lowered the coefficients of its variation compared to rainfed rice (from 48% to 38%). Vegetable irrigation in the dry season was even more profitable. The optimal cropping strategies identified by bioeconomic models mainly combined multiple rainfed crop choices with balanced irrigation allocation between rice and vegetables, enabling food self-sufficiency and increased income level and stability. A pond storage capacity of 5000 m^3 was sufficient to secure these benefits under the observed climate fluctuations. The cropping strategy found to produce sufficient financial increments to achieve mid-term (8–12-years) payback of pond investment under the same level of risk that smallholders accepted under rainfed systems is among the most advisable.

1. Introduction

Sub-Saharan Africa (SSA) is one of the most vulnerable regions to current and future climate variability (Seipt et al., 2013). Along with the growing population pressure, the anticipated climate impact challenges agricultural sustainability and food security, calling for changes in existing production systems and infrastructure (Müller et al., 2011). Therefore, adaptation strategies that shield farmers, especially smallholders with limited adaptive capacity, from the detrimental effects of climate change have recently been heavily discussed in the scientific community (e.g., Connolly-Boutin and Smit, 2016; Thompson et al., 2010).

As agriculture in SSA is predominantly rainfed and vulnerable to rainfall variability, irrigation is a planned adaptation that has received attention (Faramarzi et al., 2013; Nkonya et al., 2015). African smallholders largely allocate their limited farm resources to cereal production during the rainy season for subsistence, but their productivity is stagnant and prone to decrease due to recurrent dry spells (Barron et al., 2003). As an effective measure to address this issue, smallholder irrigation holds excellent potential for expansion, for which small reservoirs are among the most useful (Xie et al., 2014). Especially under semi-arid environments, supplementary irrigation using small reservoirs effectively mitigates these climatic risks in cereal production (Fox et al., 2005; Muluneh et al., 2017). Reserved water may also be used for high-value irrigation farming, such as horticulture, to increase income during the dry season (Fox et al., 2005). The fact that reservoirs build resilience to floods and droughts that persistently exacerbate soil erosion and water insecurity may also encourage their usage.

To date, the roles of reservoir usage in handling climate-induced water stress and mitigating food insecurity and poverty in SSA drylands have been primarily assessed ex-ante using bioeconomic (or hydroeconomic) impact models (Baah-Kumi and Ward, 2020; Sanfo et al., 2017; Wossen et al., 2014). These model results are highly encouraging and informative in forming alternative water development and irrigation plans to guide pro-poor climate adaptation, whereas practical feasibility is less informed, as adequate field experimentation is lacking. Addressing this gap is critical given the technological and participatory challenges compromising the existing hydraulic schemes; the actual performance of small reservoir-based irrigation and adaptation to climate change is increasingly challenged due to the limited storage capacity and competing water demands of the growing population (Sekyi-Annan et al., 2018). Understanding smallholders' risk attitudes is also necessary to explore acceptable adaptation mechanisms. While the potential of planned adaptations, including irrigation, to enhance adaptations of poor farm households in SSA is fully acknowledged (Wineman and Crawford, 2017; Wossen et al., 2018), the practical question of how to allocate their limited farm resources to efficiently enhance the overall benefit within the limits of risk they can manage is mostly pending. Additionally, adequate consideration of possible conflicting interests between farmers and policymakers is necessary to identify acceptable strategies. For instance, the specific irrigation cropping strategies that remain to be chosen by farmers would not convince irrigation policymakers if these strategies are too risk-averse to produce enough financial return for investment payback. Smallholder farmers in SSA are mostly risk-averse, while irrigation interventions, including reservoir schemes, are highly capital-intensive.

Therefore, identifying the strategic compromises between farm risk management and investment payback is key to (re)directing adaptation pathways.

This chapter presents new reservoir-based irrigation cropping strategies that address the unsettled technological challenges, participatory breakthroughs, farm risk management, and investment justification, drawing on the findings from Koide et al. (2021). As a technological contribution, they first developed a new pond system to resolve the issue of competing water demands. Then, they examined the practical feasibility of planned irrigation using the pond system based on replicated participatory on-farm trials and surveys. Using multidisciplinary data from trials and surveys, they further constructed empirical bioeconomic models to better allocate pond water and other farm resources. The models are designed to identify the optimal irrigation cropping strategies that are the most efficient in securing food and the income of smallholders and resilient to the observed climate fluctuations. They finally compared these strategies to identify the most advisable strategy regarding farm risk management and investment payback of the new pond system (Koide et al., 2021).

They introduced the pond system in pursuit of lowland rice and vegetable irrigation development in the semi-arid region of northern Ghana. Rice is a target crop because, among other cereals, rice consumption sharply increases in SSA (Zenna et al., 2017), and rice is relatively sensitive to water stress, especially during the reproductive stage; thus, supplementary irrigation is crucial. We also target dry-season vegetable gardening, offering smallholders additional opportunities to benefit, considering that SSA's declining per-capita land holding size underscores the importance of small-plot horticultural irrigation development (Burney and Naylor, 2012). The semi-arid region of northern Ghana, especially the peri-urban region, is increasingly populated and dominated by smallholders. Small irrigation development in this region has long received attention due to the persistent water-related poverty associated with erratic rainfall (Balana et al., 2020; De Pinto et al., 2012).

2. Material and methods

2.1 Data collection

2.1.1 Description of the study area

Koide et al. (2021) said participatory on-farm trials and surveys were conducted in a community approximately 15 km northwest of Tamale. This area was selected as its agriculture is predominantly rainfed and severely affected by changing climates. Over the past decades, the area has experienced increased weather extremes, such as heavy rainfall, long-lasting heat waves, and a relatively rapid increase in the mean annual temperature (USAID, 2017). Moreover, highly variable rainfall coupled with high evaporation rates further increases farmers' vulnerability and necessitates adaptations. Rainfall in Tamale, which mostly ranges from 800 mm to 1,200 mm per year, occurs during the single cropping season, during which dry spells frequently occur at the critical growth stages of major food staples and severely affect their yields (Kranjac-Berisavljevic et al., 2014). The projected decrease in the total annual precipitation, the delayed onset of the wet season, and the shortened growing season could further limit the yield potential. Researchers estimate that the yields of the major rainfed crops grown in northern Ghana could decrease by 25% by 2050 if no adaptation measures are taken (Nutsukpo et al., 2013). These threats imply the need for supplementary irrigation and suitable cropping schedule adjustments to stave off food insecurity in this area. In particular, marked demands exist for investing in small-scale supplementary irrigation using rainwater-harvesting reservoirs as a recommended adaptive strategy to the changing climate (Kemeze, 2020). The selected community has one of the most common types of small rainwater-harvesting reservoirs locally available, namely, dugouts, along with the typical rainfed farming environments surrounding it (Koide et al., 2021).

Dugouts in northern Ghana abound across communities, and both dwellers and herders access dugouts as a major water source for survival (Namara et al., 2011). However, due to the limited storage capacities, many dugouts overflow during the rainy season, whereas they nearly dry up during the dry season. In Nwogu, the overflow from the dugout has caused extensive gully erosion, while its water depletion has precluded cropping during the dry season, as no other exploitable water resources are available in the community. Thus, to secure food production and break this intractable cycle, the community was proposed to establish a hydrological mechanism to control the dugout overflow and simultaneously implement rainy season supplementary irrigation, soil erosion prevention, and dry season water shortage mitigation. The community accepted the proposal (Koide et al., 2021).

2.1.2 Description of the pond irrigation system

With community approval and after topographical and hydrological investigations conducted in 2014, a small subpond (5,000 m^3) and an intake canal that connects the subpond and dugout were constructed (Figure 1). During the rainy season, excess water from the dugout flows to the subpond to prevent erosion and store water for timely irrigation to bridge the dry periods, while the dugout continues to serve as the principal domestic and livestock water source. Therefore, this system, which is based on a pair of ponds (a “paired-pond system”), allows farmers to harness water for irrigation without making tradeoffs with other water uses (Koide et al., 2021).

In northern Ghana, the paired-pond system contrasts the conventional small reservoir irrigation schemes susceptible to other competing water demands (Sekyi-Annan et al., 2018). The system is not relatively massive or sumptuous. However, the storage capacity of the subpond is sufficient to achieve the most from the excess dugout water. More details regarding the concept, design, and technological features of the paired-pond system are described in the technical manual (JIRCAS, 2017).

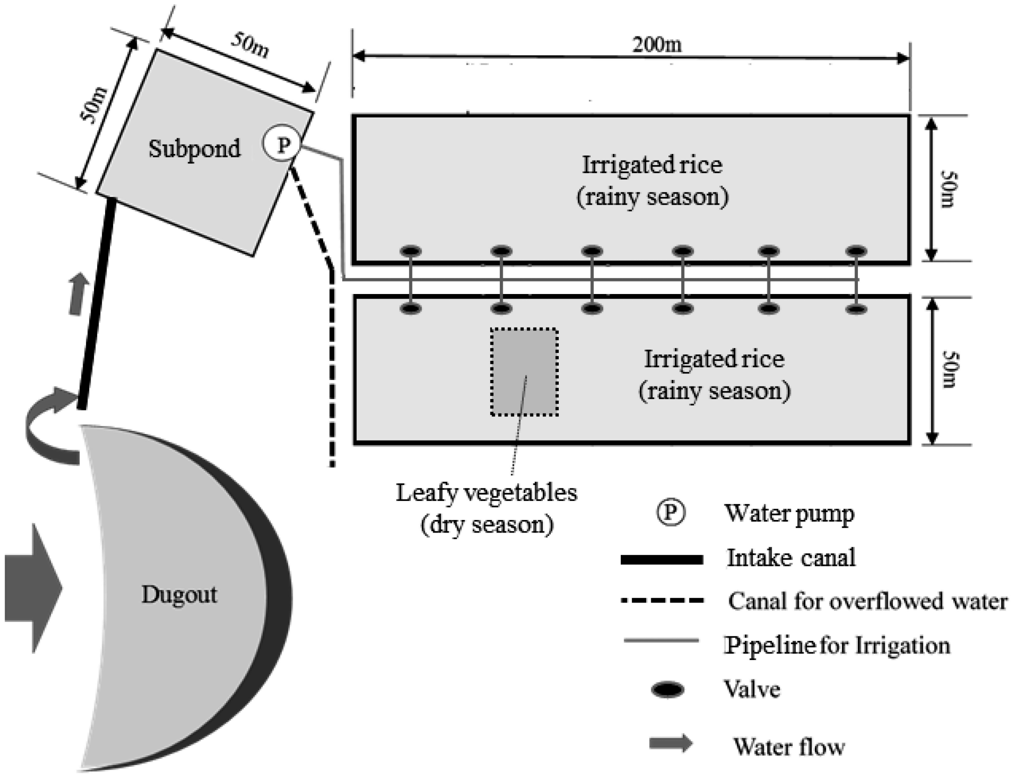

Figure 1. A schematic picture of the paired-pond irrigation system
Source: Koide et al. (2021)

2.1.3 On-farm trials and surveys

After introducing the paired-pond system in 2014, on-farm trials and surveys were conducted annually until 2019. Following our instructions, the trial farmers, who consisted of 30 representative smallholders in the community, consistently managed field operations, including irrigation for rice and leafy vegetable production, to demonstrate agronomic and economic performance with their technical capacities. During the rainy season, the farmers applied supplementary irrigation to 2 ha of rice fields, which were initially estimated to be irrigable within the subpond capacity, followed by the full irrigation of 0.12 ha of leafy vegetable plots with the remaining water during the dry season. These irrigated areas developed alongside rainfed areas where the trial farmers conventionally grew maize, rice, and pepper (Koide et al., 2021).

In parallel with the on-farm trials, detailed agronomic information regarding the trial fields and other conventional crop fields was gathered over five years (2015–2019). Based on careful instructions regarding the installed materials delivered to the trial farmers, the farmers recorded the daily amounts and costs of the inputs (seeds, fertilizer, herbicide, insecticide, and materials and fuel for irrigation) and services (tractors and vehicles) that they used, the volume of water that they irrigated, and the number of persons, hours, and wages paid for each crop production. The extensionist monitored and assisted in the recording activities every few days and cross-checked the data before we double-checked the data for approval. The accumulated data allowed us to precisely quantify the farmers' actual production costs for each crop across years and the volumes and timelines of irrigation and labor use. Each crop's plot size and harvest quantity were also measured yearly for the yield evaluation. With installed instruments, including meteorological observation equipment and water gauges, the in situ daily precipitation, temperature, water depth of the subpond, groundwater recharge, and evaporation and leakage levels were also monitored to capture the sequential water balances. Detailed socioeconomic information regarding the trial farmers' household demographic composition, labor, crop preferences, consumption, and sales was collected by directly observing their housing conditions and administering a structured questionnaire. All agronomic, hydrological, and socioeconomic data were comprehensively used to construct the empirical model specified in the following subsection (Koide et al., 2021).

2.2 Model specification

Among the various modeling techniques available for assessing climate adaptation mechanisms, Koide et al. (2021) employed multiple-purpose bioeconomic modeling combined with MOTAD (the minimization of total absolute deviations), which is a risk programming technique, for the following reasons. First, mathematical programming continues to be highly useful for optimizing farm-level activities in the face of climate change, but integration of the risks is limited in the literature (van Wijk et al., 2012). Although risk or stochastic programming approaches have long been applied for agricultural system optimization in developing regions (e.g., Maleka, 1993; Nanseki, 1991; Torkamani, 2005), these approaches are rarely applied in smallholder adaptation studies in SSA, including bioeconomic modeling work. Second, MOTAD linearizes the objective function and enables risk programming with lower computational costs than other nonlinear optimization algorithms (Hazell and Norton, 1986). This increases the model's applicability, as MOTAD and its variants are widely used to analyze risk-efficient agricultural systems (e.g., Adesina and Ouattara, 2000; Mesfin, 2014; Osaki and Batalha, 2014; Umoh, 2008). Finally, smallholders pursue multiple purposes, including risk mitigation and income and food security, to survive in a changing climate. A comprehensive examination of the existing bioeconomic models (Castro et al., 2018) supports the notion that multiple-objective robust models that address uncertainty and complexity are applicable and warrant more attention in future research.

The model used in the study is specified as follows:

$$Min \sum_{h=1}^{s} d_h \tag{1}$$

s.t.

$$\sum_{j=1}^{n}(c_{hj} - \bar{c}_j)x_j + d_h \geq 0,\ for\ all\ h, h = 1,2,\dots,s \tag{2}$$

$$\sum_{j=1}^{n} y_j x_i \geq f_j \tag{3}$$

$$\sum_{j=1}^{n} a_{ij} x_j \leq b_i,\ for\ all\ i \tag{4}$$

$$w_p - w_{p-1} - \sum_{j=1}^{n} r_{jp} x_j - g_p = 0,\ for\ all\ p, p = 1,2,\dots,m \tag{5}$$

$$0 \leq w_p \leq 5000,\ for\ all\ p \tag{6}$$

$$d_h,\ x_j\ \geq 0,\ for\ all\ h, j \tag{7}$$

where d_h is the absolute value of the negative deviations in the total net income in year h, x_j is the area of production j, including that of irrigated rice, leafy vegetables, maize, and pepper, c_{hj} is the net income of production j in year h, $\bar{c}_j$ is the mean of the net income of production j, yj is the yield of production j, f_j is the household food self-sufficiency requirement of production j, a_{ij} is a technical coefficient that captures the level of the use of farm resource i, including land and labor, for production j, b_i is the available farm resource i, w_p is the water volume of the subpond during period p, which is determined by the day, r_{jp} is the irrigation coefficient of production j during period p, and g_p is the water balance of the subpond without irrigation during period p (Koide et al., 2021).

Given the increased farm vulnerability to income loss following climate change, the main goal of planned adaptations, including irrigation, is to improve farm risk management and establish income stabilization (Smit and Skinner, 2002). The objective function, therefore, is designed to address the downside income risk, with the expected income parameterized to maintain or exceed the income from conventional practice. To simultaneously condition the household self-sufficiency of major local food staples, Eq. (3) is introduced. Since household's dietary preferences influence cropping decisions and mainly involve maize and rice at our study site (Shiratori, 2019), Eq. (3) is designed to meet the self-sufficiency of the respective two crops. Overall, the model outputs solutions that can most efficiently manage income risk and meet food self-sufficiency subject to the constraints of farm resources, such as land and labor, as referenced in Eq. (4), and water resources for implementing pond irrigation, as specified in Eqs. (5) and (6) (Koide et al., 2021).

Since trial farmers use the pond jointly, the model is applied to the entire group of farmers. Different cropping strategies and their impact are illustrated based on five models. Following the observed land allocation by the trial farmers, Model (1) mimics the conventional mode of practices; rainfed production covers all cultivated areas, including 2 ha of trial rice fields during the rainy season with no vegetables grown during the dry season. In contrast, the other four models allow paired-pond irrigation options, including the supplementary irrigation of rice and the full irrigation of leafy vegetables, to be added to evaluate their effects. Specifically, Model (2) examines the effects of minimizing income fluctuations with the same expected income as that in Model (1). Model (3) minimizes income variation regardless of the income level to explore a more risk-averse solution. Model (4) addresses the potential of paired-pond irrigation to enhance income with the same variation as that in Model (1). Model (5) determines the maximal income level regardless of the variation (Koide et al., 2021).

Additionally, the extent to which the respective irrigation strategies derived from Models (2)–(5) are sensitive to climate variability is examined. Since farmers are particularly sensitive and more likely to adapt to interannual variability than long-term changes in climatic conditions (Berrang-Ford et al., 2011), Models (2)–(5) were applied to the five climate regimes observed in the respective years of the investigation to determine whether these irrigation strategies are resilient to interannual climate fluctuations. However, even if the strategies are resilient, they should be rejected if it is financially impossible to sustain the irrigation schemes. In particular, irrigation strategies under Model (2), which target the same expected income as conventional rainfed production under Model (1), are unlikely to accumulate financial increments to recoup irrigation investment. To determine whether other irrigation strategies under Models (3)–(5) are financially viable, the following net present value (NPV) by model is computed:

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_0 \tag{8}$$

where C_t is the net cash inflow during period t, C_0 is the total initial investment cost, and r is the discount rate. C_0 fully covers the capital investments implemented to establish the new pond irrigation system, including constructing the subpond and canals, fencing, pump, pipeline, and land reclamation. C_t is the difference between the expected financial gains from irrigation strategies and the required facility maintenance costs (desilting, renewal of fences, pumps, and pipelines). r ranges from 0.1 to 0.15. Ghana’s inflation rate during the last decade (2010–2019) was mostly between 10% and 15%, with an average of 11.6% (World Bank, 2020). The discount rates used to assess other irrigation investments in Ghana (e.g., Balana et al., 2020) and other African countries (e.g., You et al., 2011) also fall within that range.

3. Results

3.1 Rainfed and irrigated cropping performance

The cropping performance shown in Table 2 underscores that pepper provides the highest income among other crops but with the highest variation. It is, therefore, inadvisable for farmers to rely exclusively on this cash crop to secure income. Maize, a major food staple, also involves a relatively high variation in income, mainly due to yield instability. Thus, it is also inadvisable for farmers to rely exclusively on it to secure food. In contrast, yields of rainfed rice are relatively stable. In addition, the average income from rainfed rice is higher than maize and lower than pepper but lower than maize and pepper in terms of income variation. These results imply that conventional rice production mitigates the food and income risks related to maize and pepper production, respectively (Koide et al., 2021).

Irrigated rice and leafy vegetables outperformed conventional crops. By using supplementary irrigation, the trial farmers achieved higher rice yields with a slight increase in the coefficient of variation (CV) (from 17% to 23%) and higher income with a decrease in the CV (from 48% to 38%) compared to rainfed rice. Furthermore, the income from leafy vegetables is comparable to the income from pepper but is much less varied, as the CV of leafy vegetables (47%) is lower than that of pepper (88%). Since irrigation competes between rice and vegetables, water allocation to these two profitable (and low-risk) crops is highly important to benefit from the paired-pond system (Koide et al., 2021).

Efficient labor allocation between rainfed and irrigated crops is also important to benefit from the pond system. By comparing the actual labor inputs (Table 3), we observe that irrigated rice is less labor-consuming than rainfed rice. This result is due to effective weed control from cropping schedule adjustment and timely irrigation. While sowing with the advent of rainfall requires substantial care for the first weeding for rainfed rice (from June to July), irrigated rice requires less labor due to late plowing. Because this scheduling enables timely irrigation from the subpond during the critical period (approximately October), it also facilitates field submergence to better control weeds and allows farmers to save on labor for reweeding. During the same period, rainfed rice, maize, and pepper are ready for harvesting. After this period closes in November, irrigated rice is ready for harvesting. Therefore, farmers can reallocate the labor saved in weed control for irrigated rice to harvest rainfed crops followed by irrigated rice without hiring additional labor. Therefore, shifting the rice sowing dates helps farmers increase rice production (and income) and maintain maize and pepper production, multiplying their food and income sources (Koide et al., 2021).

Table 2. Trial farmers' crop yield, price, and net income

		Yield (t/ha)	Price (GHS/kg)	Net income (GHS/ha)
Rainfed rice	Mean	3.12	1.10	1,282
	CV (%)	17	12	48
Maize	Mean	1.48	0.91	621
	CV (%)	42	13	82
Pepper	Mean	1.69	4.59	4,536
	CV (%)	70	35	88
Irrigated rice	Mean	3.84	1.10	3,027
	CV (%)	23	12	38
Leafy vegetables	Mean	1.01	8.30	4,090
	CV (%)	33	27	47

CV: Coefficient of variation

Source: Koide et al. (2021)

Table 3. Monthly labor inputs by crop (avg. man-hour/ha)

	Rainfed rice	Maize	Pepper	Irrigated rice	Leafy vegetables
Apr			186		
May	98	63	133		
Jun	248	105	390	130	
Jul	254	129	342	145	
Aug	152	41	224	212	
Sep	239	38	243	105	
Oct	459	62	407	87	
Nov	131		184	552	
Dec	88		140	18	
Jan					527
Feb					407
Mar					412
Total	1,669	437	2,251	1,249	1,345

Source: Koide et al. (2021)

3.2 Model analyses

The on-farm trial results suggest that efficient resource allocation to new irrigated and conventional rainfed crops improves livelihoods. However, practical questions of how and the extent to which this improvement is achievable given farmers' resource endowments, risk attitudes, and irrigation water availability remain. These questions are addressed by using the constructed models. Table 4 indicates different solutions by model. Under Model (1), farmers gain 31,117 GHS on average from conventional rainfed systems. Under Model (2), farmers maintain the same income, but its standard deviation (SD) declines by 43%. This result reflects the effect of paired-pond irrigation coupled with resource reallocation on mitigating the pervasive risk in rainfed systems without lowering the expected income level. Specifically, the bulk of pepper, the crop with the highest income fluctuation, is replaced with irrigated rice, contributing to income stability. Moreover, this solution is consistently adopted under different climate regimes. The paired-pond system appears to have the capacity to moderate climate-induced fluctuations in irrigation water availability and maintain the effect of risk mitigation. Since supplementary irrigation alone (without dry-season irrigation) is sufficient to mitigate risk, Model (2) allows some subpond water to remain until the end of the season (March), regardless of the climate regime (Figure 3). Although the subpond is primarily used for irrigation, the remaining water may be used for non-irrigation when necessary (Koide et al., 2021).

However, the solution under Model (2) is suboptimal, as the solution under Model (3) presents higher income with a lower variation consistently across the five climate regimes. As reflected in the crop combination, the key is introducing leafy vegetables coupled with irrigated rice. Therefore, farmers can reduce risk and enhance income with irrigated crops incorporated into the cropping system. However, if the risk of conventional rainfed systems is still acceptable, farmers may prefer the solution under Model (4), which yields a total income approximately 50% higher than that under Model (3). This substantial gain can be obtained after fully expanding the irrigated rice and vegetable areas under subpond water availability. Therefore, under Model (4), the subpond always dries up by the end of the season. Pepper cultivation also scales up at the expense of maize cultivation within the limit of satisfying the maize self-sufficiency requirements. This increased reliance on pepper raises the income risk, but expanding irrigated crop areas buffers such risk. As for the solution under Model (5), the pepper area further expands instead of the rice area within the limit of meeting the rice self-sufficiency requirements, boosting the total income by approximately 30% compared to that in Model (4). However, the variation in income increases to a greater extent and could be intolerable for farmers, considering the actual level of income risk they accept in conventional rainfed systems (Koide et al., 2021).

Table 4. Results of the model analyses

Model	Climate regime	Rainfed rice (ha)	Maize (ha)	Pepper (ha)	Irrigated rice (ha)	Leafy vegetables (ha)	Expected net income (GHS)	SD (GHS)	CV (%)
(1)	-	8.03	11.41	2.82	-	-	31,117	11,968	38.5
(2)	2014-15	7.22	13.45	0.67	0.93	0	31,117	6,788	21.8
	2015-16	7.22	13.45	0.67	0.93	0	31,117	6,788	21.8
	2016-17	7.22	13.45	0.67	0.93	0	31,117	6,788	21.8
	2017-18	7.22	13.45	0.67	0.93	0	31,117	6,788	21.8
	2018-19	7.22	13.45	0.67	0.93	0	31,117	6,788	21.8
(3)	2014-15	9.12	11.69	0.73	0.72	0.72	36,354	6,122	16.8
	2015-16	9.12	11.69	0.73	0.72	0.72	36,354	6,122	16.8
	2016-17	9.12	11.69	0.73	0.72	0.72	36,354	6,122	16.8
	2017-18	9.12	11.69	0.73	0.72	0.72	36,354	6,122	16.8
	2018-19	8.79	11.90	0.71	0.87	0.51	35,307	6,224	17.6
(4)	2014-15	7.84	9.86	3.78	0.79	0.79	49,853	11,968	24.0
	2015-16	7.89	9.86	3.76	0.75	0.75	49,591	11,968	24.1
	2016-17	7.55	9.86	3.86	0.99	0.99	51,206	11,968	23.4
	2017-18	7.93	9.86	3.75	0.73	0.73	49,441	11,968	24.2
	2018-19	8.03	9.86	3.72	0.65	0.65	48,959	11,968	24.4
(5)	2014-15	3.65	9.86	7.96	0.79	0.79	64,623	29,276	45.3
	2015-16	3.70	9.86	7.95	0.75	0.75	64,392	29,286	45.5
	2016-17	3.41	9.86	8.01	0.98	0.98	65,797	29,234	44.4
	2017-18	3.73	9.86	7.95	0.73	0.73	64,263	29,290	45.6
	2018-19	3.82	9.86	7.93	0.65	0.65	63,830	29,310	45.9

SD: Standard deviation of the expected net income

CV: Coefficient of variation of the expected net income

Source: Koide et al. (2021)

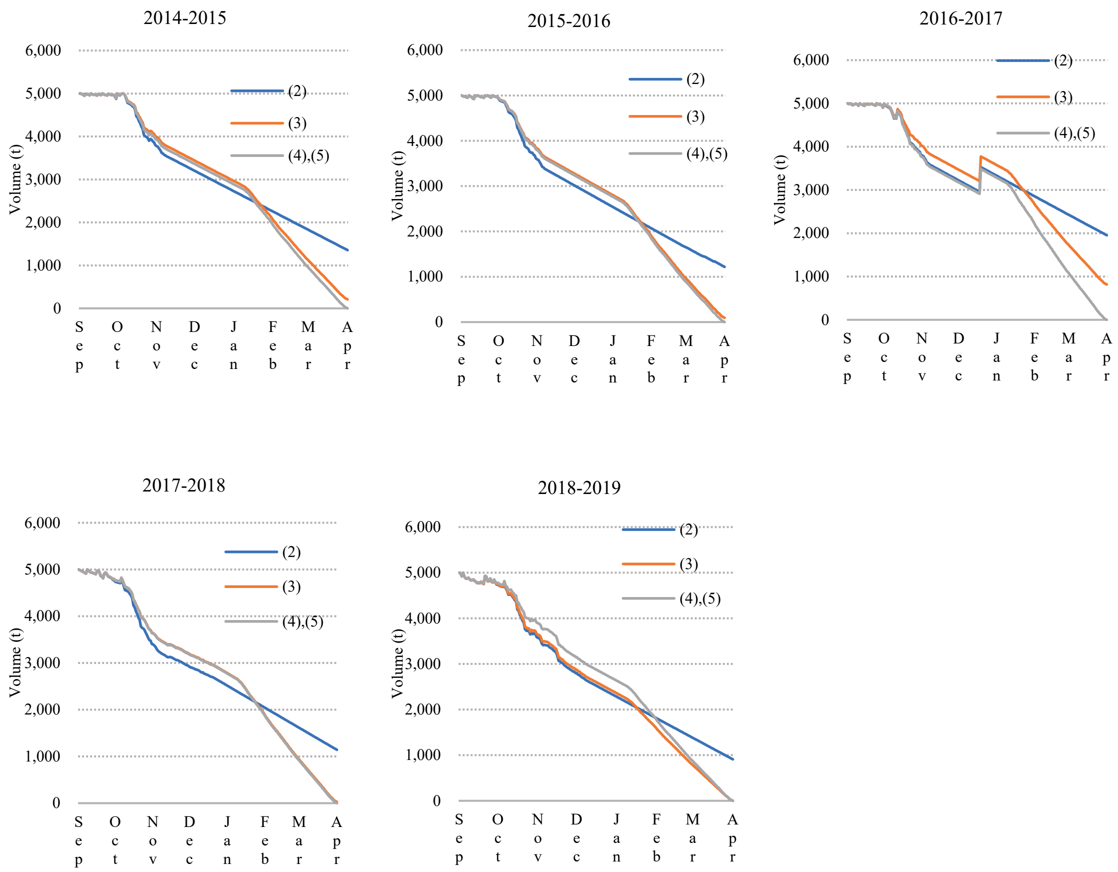

Figure 3. Sequential subpond water volume by model and climate regime

Source: Koide et al. (2021)

The above results support the striking effects of irrigation cropping alternatives on mitigating the risks of conventional rainfed systems and/or increasing income. However, not all alternatives demonstrate the economic viability of the paired-pond system. Figure 4 indicates that by relying on the minimal risk solution under Model (3), farmers will find it difficult to obtain a positive NPV. Although Model (3) increases income, the gains are too small to cover all the costs required for the paired-pond system. In contrast, the maximal income solution under Model (5) makes the NPV positive by year four. Although such a short-term recovery is better able to reduce uncertainty, the solution under Model (5) could be too risky for farmers, as mentioned in the previous section. The solution under Model (4) is more realistic; this solution obtains a positive NPV within 8 to 12 years at the same risk level as conventional systems (Koide et al., 2021).

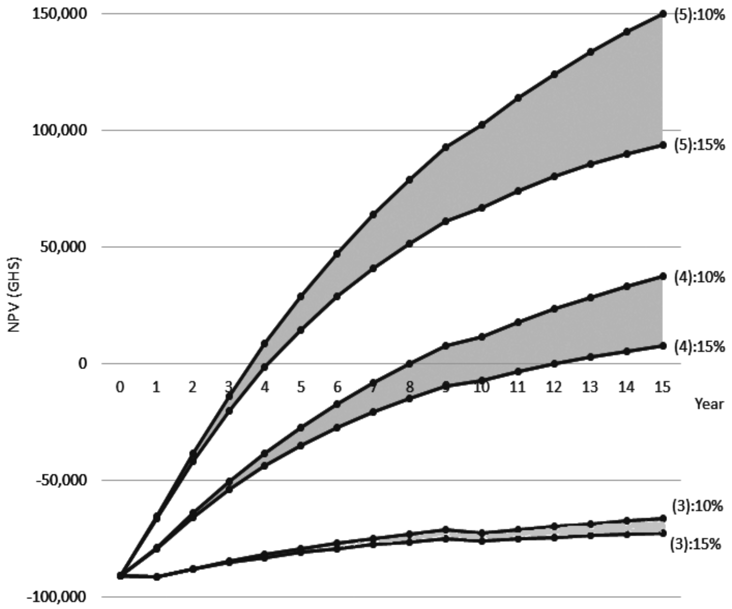

Figure 4. NPV by model and discount rate

Source: Koide et al. (2021)

5. Conclusion

The paired-pond system approach upgrades the supplementary irrigation techniques by reharvesting the seasonal overflow from a preexisting rainwater-harvesting dugout. Years of participatory on-farm experimentation of this system demonstrate that it can serve as an effective adaptation platform, enabling the increased level and stability of crop yields and profitability among farmers. Results from model analyses highlight that the optimized mixes of multiple rainfed crop choices with planned irrigation to rice and vegetables effectively meet household food demands and increase the total income. The results also indicate that farmers can consistently achieve these benefits under the observed climate fluctuations. However, the new irrigation strategies farmers will most likely benefit from while recovering their investment costs vary by risk attitude. In the case of the paired-pond system with the most risk-averse solution (Model (3)), yielding sufficient economic returns to sustain irrigation schemes is difficult. In contrast, the maximal income solutions (Model (5)) enable short-term cost recovery but marginalize farmers who cannot accept greater risk than that incurred under rainfed systems. Realistic solutions include those with the same risk level and sufficient financial increments to achieve mid-term payback (Model (4)). Therefore, these solutions may be recommended to farmers and policymakers to develop concerted adaptation actions (Koide et al., 2021).

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Chapter 4 Issues and model-based optimization of smallholder technology adoption in livestock systems: Case of dairy technology in southern Mozambique

4-1 Challenges for the sustainable adoption of smallholder dairy farming: A post-intervention study in southern Mozambique

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Abstract

Dairy promotion and support for farmers through international livestock donation programs have been increasingly implemented to enhance milk production and meet the growing demand in Africa. However, it remains insufficient to explore whether farmers have successfully established sustainable dairy systems post-intervention. This chapter presents the findings from Koide et al. (2020) and Koide and Tinga (2021), which examined the persistence of milk production and its limitations in southern Mozambique, where farmers received Jersey cattle as part of a dairy development program. These studies meticulously tracked the dairy cattle recipients and assessed their feeding, health, reproductive management practices, and economic performance based on data from questionnaire surveys. The results highlight that the cattle recipients progressively abandoned milk production due to challenges in disease control and breeding failures. While short-term benefits emerged from low-cost dairy operations, deficiencies in feeding, housing, and healthcare negatively impacted cow fertility, productivity, reproductive performance, and survivability, ultimately preventing any long-term gains. Comparative analysis of different farm models further revealed that while more profitable, small family farms operate in unsustainable ways compared to larger commercial farms. In light of these findings, this chapter underscores the urgent need to strengthen institutional, technical, and educational support for animal disease control and reproductive management to foster a conducive environment for sustainable dairy production, particularly for smallholder family farms.

1. Introduction

Among livestock products, dairy products such as milk are expected to see a significant increase in consumption across Africa (Herrero et al. 2014). However, production levels remain stagnant. In 2017, statistics showed that while Africa's dairy cattle population constituted about 26% of the global total, its share of milk production was less than 6% (FAO 2019). Additionally, over 70% of this production is concentrated in the northern and eastern regions, with other areas, particularly the southern countries excluding South Africa, showing uniformly low production levels.

Mozambique is no exception. The country's demand for milk is increasing, especially in urban areas, yet it remains heavily reliant on imports from South Africa and Europe, underscoring the need to boost domestic milk production. The small family farming sector, which constitutes the majority of domestic agricultural producers, has considerable potential for enhancing milk production. However, their livestock farming primarily focuses on poultry and goats, with limited involvement in cattle rearing. Furthermore, the cattle are predominantly indigenous breeds utilized for meat and labor rather than milk production. Consequently, recent years have witnessed the introduction and expansion of dairy cattle farming across various regions of Mozambique. Notably, with support from the U.S. Department of Agriculture, Land O' Lakes (hereafter LOL) provided Jersey cattle from South Africa to central and southern Mozambique farmers between 2009 and 2016 (Vernooij et al. 2016).

The importation of Jersey cattle was accompanied by training in rearing techniques, milk production, and marketing support (Vernooij et al. 2016). While this series of dairy development projects enabled an increasing number of farmers to enter the dairy sector and enhanced their incomes (Johnson et al. 2015), it remains unexplored whether dairy farming has been sustainably established following the completion of the project. Although some emerging challenges, including those related to feed formulation and milk value chain, have been documented (Vernooij et al. 2016), there has been insufficient analysis of the challenges related to dairy cattle management encountered by farmers, including breeding and healthcare difficulties. This chapter presents the findings of Koide et al. (2020) and Koide and Tinga (2021), who conducted a post-intervention study of dairy promotion in southern Mozambique and examined the practical constraints on sustainable milk production among farmers.

2. Materials and methods

Field surveys were conducted in the Manhiça District of Maputo Province, where LOL initiated dairy development between 2013 and 2016. Situated approximately 60 km north of Maputo city, the Manhiça District is relatively land-scarce, with a population density of 86 persons/km² (INE, 2017). Most farmers are smallholders who cultivate small, fragmented plots and rear a limited number of ruminants and poultry. In addition to the Jersey cattle provided by the dairy development program, a few households raise indigenous cattle (Landim) for meat and traction purposes. Other ruminants, such as goats and sheep, are generally not lactated. Therefore, local farmers, including the recipients of the Jersey cattle, had no prior experience with milking before the dairy development program. The farmers received technical training and marketing support for dairy production during the program. Moreover, feed storage and milk processing facilities were established, and equipment such as homogenizers and sterilization tanks were supplied. A dairy farm association was formed to manage the shared use of these facilities and equipment and coordinate milk collection, sales, and breeding activities (Koide and Tinga, 2021).

In 2019, the dairy farm association obtained historical data on the number of dairy farms and Jersey cattle. The changes in numbers between 2016 (the end of the dairy development program) and 2019 (the time of the survey) were analyzed to assess the continuity of dairy production after the project's completion. The primary reasons for discontinuation were identified through interviews with all farms that had ceased dairy production. Conversely, all farms that continued dairy operations were also interviewed to assess their management practices. Data on cattle holdings, feed composition, disease control measures, reproductive status, lactation yields, and milk sales were collected using a structured questionnaire to evaluate their farm management practices and performance. In addition, the continued farms were categorized by farm type and compared to examine the differences in dairy management practices and performance. Mozambique's livestock statistics classify domestic dairy farms into "Sector Familiar" and "Sector Privado" (referred to as Types A and B), and the comparison was made according to this classification. As detailed in the following section, Type A consists of small family dairy farms that primarily rely on family labor, while Type B includes commercial farms that entirely depend on hired labor and maintain relatively larger herd sizes. The scale of crop farming also differs between the two types. Type A farms typically operate on 1–2 hectares, cultivating a diverse range of crops such as maize, cassava, groundnuts, sugarcane, sweet potatoes, and bananas, and they do not possess agricultural machinery, instead working on multiple small plots. In contrast, Type B farms have larger operational areas, particularly in the lowlands, and some utilize agricultural machinery for monoculture sugarcane farming on tens of hectares (Koide et al., 2020).

3. Issues of local dairy farming

3.1 Continuity of dairy farming

During the dairy development program, imported Jersey cattle were distributed across 66 farms in the Manhiça District. Along with four additional farmers who acquired heifers from these farms, there were 70 dairy farms as of 2016. Most farms kept only one cow, while a very small number owned bulls. According to the local dairy association, farmers paid 1,200 Meticais to receive a pregnant heifer from the LOL project. Despite the conclusion of the project, farmers could still obtain heifers by paying the same fee to the dairy association. Initially, the offspring of these heifers were intended to be sold to new participants, but this did not transpire as expected. The total number of dairy farms in the Manhiça District declined from 70 in 2016 to 18 in 2019, with most recipients of the Jersey cattle exiting milk production and only one new farm entering the industry. The cattle population also witnessed a significant reduction during this brief period (Table 1).

Table 1. Changes in the number of dairy farms and cattle population in Manhiça District

	2016	2019
Number of farms	70	18
- Cow/Heifer	81	32
- Bull	8	6
- Calf	64	25

Source: Koide and Tinga (2021)

The successive disadoption of dairy farming can largely be attributed to the cattle's low survival and reproduction rates. Farmers who discontinued milk production reported reasons such as animal mortality due to disease or accident (63%), abandonment through sale or transfer (30%), and theft (7%). Animal deaths were frequently caused by diseases such as tick-borne illnesses, while cattle theft increased due to supply shortages and rising meat prices in urban areas, exacerbated by foot-and-mouth disease. Although efforts were made to expand herd sizes, artificial insemination remains underutilized, and with the diminishing number of dairy farmers, sourcing bulls has become increasingly challenging, creating a bottleneck in reproduction. Furthermore, the rising incidence of animal sales and transfers indicates that herd reproduction and renewal are stagnating, leading to mere culling. The limited influx of new entrants can also be explained by these challenges in breeding (Koide and Tinga, 2021).

3.2 Breeding and health issues

The persistent issues of animal disease and reproductive inefficiencies continue to affect the remaining 18 dairy farms. Cow fertility has stagnated, with an average calving rate of only 67%. Limited access to breeding systems exacerbates reproductive challenges. Due to long distances, artificial insemination (AI) services have reached only a small number of farms and have rarely resulted in successful conception due to poor semen quality. These limitations on AI expansion mean that many farms continue to rely on natural mating. However, the reduced cattle population and inaccurate heat detection prevent the remaining farms from mating their cows at optimal times. As a result, the average calving interval has extended to 781 days, significantly longer than intervals reported in comparable production systems (e.g., Banda et al. 2012). Moreover, the average mortality rates for calves and cows are 17% and 22%, respectively. The primary causes of mortality are consistent with those experienced by farms that exited the industry, including tick-borne diseases and accidents (Koide and Tinga, 2021).

Given the persistent challenges in breeding and health management, the current herd structure is unsustainable through internal reproduction. With a calving interval of 781 days, each cow produces only 0.23 heifer calves per year, assuming an equal sex ratio. With an observed calf mortality rate of

17%, only 0.19 calves survive to become heifers, and their 78% survival rate leaves only 0.15 cows available for lactation before culling. To establish a sustainable reproductive cycle, each cow would need to produce at least seven offspring (lactations), which is practically unfeasible given the prolonged calving interval. Since a farm has fewer than seven cows, the current farms cannot produce enough heifers to maintain herd replacement. This limitation prevents farms from replicating lactations and capitalizing on the sale of breeding stock to enhance income or accelerate culling to improve herd genetics. The absence of surplus stock also limits potential collaboration with non-dairy farms and hinders complementary transactions among the existing dairy farms. Unless health and reproductive management practices are improved, smallholder dairy expansion and sustainable production will remain unachievable (Koide and Tinga, 2021).

3.3 Feed and sanitary issues

Attention must also be given to animal feeding and sanitation practices. The remaining 18 dairy farms house Jersey cattle in kraals, with the majority (89%) employing a zero-grazing system, in contrast to the year-round grazing typical of indigenous cattle. Most farms (94%) utilize a cut-and-carry feeding system, primarily relying on guinea grass (*Panicum maximum*) as the main roughage and maize bran as the primary concentrate (75%). Approximately one-third (31%) of the farms have established pastures that are generally small and dominated by Napier grass (*Pennisetum purpureum*). Many farmers (72%) expressed concerns about seasonal feed shortages, particularly during the dry season, when silage and other preserved feeds are unavailable. Although year-round crop production is common, the edible portions of crops are consistently used to meet household needs. Most farms (75%) collect inedible crop residues for fodder, which is critical in supplementing protein; notably, legume and tuber crop residues provide higher crude protein content than maize bran. However, the availability of this fodder is limited due to low yields and small plot sizes. Most farms (72%) also lack access to essential supplements such as molasses and minerals. Consequently, inadequate feeding and nutrient deficiencies may impair the animals' energy reserves, reducing fertility and productivity.

These challenges may be exacerbated by poor housing and sanitary conditions, including the absence of roofing, bedding, drainage, and the accumulation of slurry—all of which are common on local dairy farms. While farmers often apply creams to their cows' udders for protection (72%), they rarely detect diseases such as mastitis due to the absence of inspection kits. Although tick control measures, such as spraying, are commonly practiced (89%), they appear insufficient to prevent infection, as spraying is done infrequently, ranging from weekly to monthly.

4. Difference between farm types

Type A farms maintain an average herd size of 1.7 cattle. In contrast, Type B farms have a significantly larger average herd size of 7.6 cattle, which can be attributed to their greater operational scale, access to feed crop residues, and the procurement of breeding bulls from institutions such as the Mozambique Agricultural Research Institute (IIAM). While the number of Type A farms is relatively higher, only two possess milking cows, and most have just one. On the other hand, Type B farms have between 1 and 6 milking cows, with an average of 3.2.

Table 1 summarizes the annual performance of dairy production by farm type. Profitability per cow is notably higher for Type A farms. The feed cost-to-income ratio is lower, reflecting greater feed efficiency. This profitability difference does not stem from milk yield but rather from the higher market price for fermented milk, which is more common on Type A farms, and from their reduced operational costs. Type B farms face higher labor costs, comprising 59% of total expenses, compared to 31% for Type A farms. The reliance on family labor in Type A farms versus the steady employment in Type B farms underscores their divergent management practices. Furthermore, Type B farms incur higher costs for purchased feed, whereas Type A farms demonstrate greater feed self-sufficiency. Medical and hygiene expenses are also lower for Type A farms.

As a result, Type A farms achieve greater profitability through cost minimization, though their income per hour is comparable to that of Type B farms. However, overall dairy income is higher for Type B farms due to their larger herd sizes. The findings suggest that while Type A farms yield higher profitability per milking cow, Type B farms derive greater overall benefits from their advantage in total income.

Table 2. Annual performance of dairy production in the Type A and B farms

	Type A	Type B
Number of farms	11	5
Number of milking cows	1.0	3.2
Milk yield (kg/cow)	1,923	1,808
Gross income (MT/head)	106,509	92,278
- Raw milk	46,761	77,213
- Dairy products	59,748	15,066
Paid-out cost (MT/head)	16,287	51,036
- Feed cost	9,656	15,038
- Hired labor cost	5,050	30,117
- Medical and hygiene costs	1,581	5,881
Working hours (/head)	3,231	1,731
Income (MT/head)	90,222	41,243
Ratio of income to gross income (%)	84.7	44.7
Ratio of feed cost to income (%)	10.3	17.7
Hourly income of family labor (MT)	27.9	23.8

Notes:

1) Annual performance per milking cow (Dec 2017–Nov 2018).

2) Type A excludes two households with no milking cows.

3) The local market for dairy cattle has not yet developed, and there have been no instances of calf sales to date. Regarding firstborn cows, there is an instance of sale through a dairy cattle farmers' association at 1,200 MT per cow; however, this transaction was facilitated by LOL and does not reflect the true market price of dairy cows or the associated transportation costs. Given these circumstances, it is difficult to determine the dairy cows' original depreciation and the calves' sales value, so they were not included in the cost. Depreciation of kraals was also not included due to the difficulty in determining the acquisition cost.

4) MT: Metical (Mozambique's currency). 1 MT=0.016 USD (November 18, 2024)

5) Differences are significant at the 5% level (t-test) for income per cow, paid-out cost per cow, and the ratio of feed cost to income. Milk yield and hourly income of family labor are not significant.

Source: Koide et al. (2020)

Notably, most farmers exiting dairy farming are from Type A farms. The decline in cattle numbers, particularly calves, is also more pronounced among Type A farms. Thus, despite achieving high profitability through cost reduction, Type A farms face an unsustainable and high-risk model of dairy farming. Specifically, reducing medical and hygiene expenditures has led to insufficient health management, such as inadequate tick control, which increases the risk of bovine diseases. Indeed, cattle deaths due to infections remain a persistent issue on Type A farms. This problem affects not only those farmers who have already exited the industry but also those who continue dairy farming. Of the 13 remaining Type A farms, 10 (77%) have experienced herd reductions due to disease-related fatalities, particularly in calf numbers. Many of these farms now only retain the single cow initially provided by the LOL project. Therefore, while Type A farms may demonstrate high profitability per milking cow, the long-term sustainability of these profits is fragile. In contrast, Type B farms have managed to maintain their herd sizes and secure stable income.

5. Concluding remarks

The recipients of dairy cattle at the study site, particularly Type A farms, have increasingly ceased milk production due to ineffective disease control and breeding challenges following the project's conclusion. While they experienced short-term benefits from low-cost dairy operations, deficiencies in feeding, housing, and health care compromised cow fertility, productivity, reproductive performance, and survival, ultimately hindering long-term gains. Although a comprehensive strategy will be necessary to reverse these trends, addressing the shortage of replacement stock should be prioritized to foster an enabling environment for sustainability. The most immediate and practical interventions may include capacity-building initiatives to improve herd management and estrus detection, thereby reducing the extended calving intervals. In the longer term, enhancing the role of artificial insemination (AI) in reproductive success will be essential; however, this will require improvements not only in semen accessibility but also in disease tolerance and feeding practices, which are currently insufficient to fully exploit the genetic potential of Jersey cattle. Until such advancements can be made, promoting crossbreeds—an approach recommended as a lesson learned from promoting exotic dairy breeds in Malawi (Baur et al., 2017)—may provide a more viable path to long-term sustainability. Considering that Type B farms demonstrate greater continuity in dairy farming, lessons from their practices, including farm expansion and commercialization, could also serve as a potential pathway toward long-term sustainability despite smallholders remaining the primary driving force for dairy development.

In the future, policy and technical support, including veterinary services for disease control, theft prevention measures, and the establishment of reproductive systems, along with educational initiatives, will be essential for ensuring the sustainability of dairy farming. Additionally, creating an environment conducive to herd expansion by increasing feed production will be critical. Given that the lack of agricultural machinery restricts the expansion of cultivated land for small farms, ensuring a reliable feed supply through crop-livestock integration will be crucial. From this perspective, it will be necessary to address the constraints of sustainable dairy farming and explore the optimal synergies between dairy and crop farming. These considerations merit attention in future research.

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4-2 Whole-farm economic analyses of smallholder crop-dairy systems in southern Mozambique

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Abstract

Dairy production has been extensively promoted among smallholder farms in sub-Saharan Africa, playing a crucial role in enhancing household food expenditure, dietary diversity, and nutritional outcomes. However, the potential to strengthen synergies and complementarities with the cropping sector to improve food security and maximize overall farm profitability remains largely underexplored. To address this, Koide and Tinga (2021) applied an integrated farm management model to investigate optimal resource allocation strategies between crop and dairy enterprises in southern Mozambique, as outlined in this chapter. Model parameters were developed using comprehensive data on crop and dairy farming conditions and performance, collected through systematic farm-based recordkeeping and chemical analyses of feed samples. The results indicate that when dairy herds and cropping systems are strategically restructured, smallholder farms can effectively meet household food requirements, fulfill the nutritional needs of livestock for sustained lactation, and increase farm income. Additionally, on-farm milk processing has the potential to further elevate income levels. Based on these findings, the chapter concludes that promoting smallholder dairy farming can yield substantial benefits by establishing enhanced breeding and marketing systems and efficient integration with cropping activities.

1. Introduction

The sustainability and intensification of smallholder dairy farming in sub-Saharan Africa (SSA) have been investigated through various approaches, including genetic interventions (e.g., genotype migration and crossbreeding), ecological processes (e.g., zero-grazing and crop-livestock integration), and socioeconomic measures (e.g., cooperative-building and market development) (Chagunda et al., 2016). These efforts have often yielded positive outcomes, with a growing number of smallholder farms gaining access to innovations in breeding, feeding, health, and marketing to enhance dairy performance (Chagunda et al., 2014; Johnson et al., 2015; Vernooij et al., 2016). Studies have shown that international livestock donation programs have played a significant role in disseminating these innovations across SSA, resulting in increased food expenditure, dietary diversity, and improved nutritional outcomes for rural households (e.g., Rawlins et al., 2014; Kidoido and Korir, 2015; Kafle et al., 2016; Jodlowski et al., 2016).

However, many initiatives lack follow-up studies to evaluate both successful and unsuccessful outcomes. Furthermore, much of the existing literature assesses dairy performance without considering potential tradeoffs with the diversified livelihoods many African smallholders rely on for their subsistence (Ellis and Freeman, 2004). Given that most smallholder dairy farms are resource-constrained and depend on self-produced feed, resulting in low levels of milk production (Bebe et al., 2008), there is an urgent need to improve the allocative efficiency of limited farm resources. This would ensure the provision of both household food and livestock feed while maximizing overall farm benefits. Whole-farm analysis is essential for achieving this goal, as it can help reassess the net impact of dairy farming on smallholder food security and welfare. However, few examples of whole-farm modeling targeting smallholder dairy farms exist in SSA (e.g., Nanyeenya et al., 2008). There is a particular need for longitudinal studies tracking past beneficiaries of livestock donation programs and modeling efficient multi-sectoral resource allocation strategies that integrate crop and dairy production.

This chapter presents findings from Koide and Tinga (2021), who conducted whole-farm analyses in the Manhiça milkshed, located in Manhiça District, Maputo Province, Mozambique. By addressing the challenges local farmers face in dairy cattle management, as outlined in the previous chapter (Chapter 4-1), they explored alternative crop-dairy resource allocation strategies and their potential to improve household food security and income levels.

2. Materials and methods

2.1. Data

To conduct the whole-farm analysis, Koide and Tinga (2021) selected a representative farm situated in the primary hub (village) of dairy development. Based on a preliminary survey of all village households, this farm was deemed representative regarding farm size, cropping systems, and livestock composition, except for the donated dairy cattle (Table 1). Systematic farm-based recordkeeping was employed over 12 months from 2018 to 2019 to collect detailed longitudinal data on all crop and livestock activities. Specifically, the representative farm documented daily the quantity and cost of inputs used (seeds, feed, fertilizer, herbicides, and insecticides), the number of workers, their hours and wages, the amount of crop harvested, and milk produced, as well as home consumption and market prices of products sold. Additionally, samples of the feed provided to the Jersey cattle were collected and subjected to laboratory analysis to determine their chemical composition (Table 2).

Table 1. Characteristics of village households and the representative farm

	Village households (n=402)	Representative farm
Household size	4.2 (Avg.)	5
Farmland holding (ha)	1.5 (Avg.)	2.1
Major crops[a]	Cassava (92%)	Cassava
	Maize (91%)	Maize
	Pumpkin (72%)	Pumpkin
	Cowpea (65%)	Cowpea
	Sweet potato (64%)	Sweet potato
	Peanut (60%)	Peanut
Major cropping pattern	Mixed cropping	Mixed cropping
Cattle[b]	0.3 (Avg.)	4
Goats and sheep[c]	1.0 (Avg.)	1
Poultry[c]	7.0 (Avg.)	9
Members with non-farm works	2.3 (Avg.)	3

[a] Crops grown by more than 50% of village households. These also constitute the major crops grown at the representative farm.

[b] A few households rear the indigenous cattle (Landim), which are not bred for dairying. At the time of the survey, the representative farm owned a Jersey herd consisting of a cow, a heifer, and two heifer calves.

[c] These animals are typically pastured around the house and used for household consumption.

Source: Koide and Tinga (2021)

Table 2. Chemical composition of feedstuffs used in the representative farm

Ingredient	DM (%)	CP (%/DM)	EE (%/DM)	NDF (%/DM)	ADF (%/DM)	TDN (%/DM)
Maize stover (*Zea mays*)	25.2	11.3	1.2	66.3	32.1	58.5
Maize bran (*Zea mays*)	86.8	13.9	10.1	29.8	8.4	84.5
Sugar cane top (*Saccharum officinarum*)	28.7	7.1	1.6	74.0	39.5	52.2
Cowpea leaves (*Vigna unguculata*)	10.8	25.5	2.6	40.6	25.6	64.5
Cowpea casks (*Vigna unguculata*)	86.5	9.1	0.4	53.2	38.2	61.2
Peanut leaves (*Arachis hypogaea*)	37.9	14.8	2.2	41.0	30.1	57.8
Sweet potato leaves (*Ipomoea batatas*)	15.4	17.8	3.9	36.0	29.8	58.6
Guinea grass (*Panicum maximum*)	35.7	9.8	1.4	72.8	40.5	55.0
Napier grass (*Pennisetum purpureum*)	19.4	12.8	2.3	67.9	36.2	56.6

DM: dry matter, CP: crude protein, EE: ether extract. NDF: neutral detergent fiber, ADF: acid detergent fiber, TDN: total digestible nutrients (%/DM)
Source: Koide and Tinga (2021)

2.2. Analysis

Using the data collected from the representative farm, Koide and Tinga (2021) constructed an integrated farm management model to analyze crop-dairy performance based on mixed integer programming (MIP). The model is specified below:

$$\max Z = \sum_{i=1}^{m} c_i x_i + \sum_{j=1}^{n} c_j y_j$$

s.t.

$$\sum_{i=1}^{m} a_{ki} x_i + \sum_{j=1}^{n} a_{kj} y_j \leq b_k, \qquad for\ all\ k$$

$$\sum_{i=1}^{m} d_{il} x_i \geq e_l, \qquad for\ all\ l$$

$$\sum_{i=1}^{m} f_i x_i \geq \sum_{j=1}^{n} g_j y_j$$

$$x_i,\ y_j\ \geq 0, \qquad for\ all\ i, j$$

$$y_j \in \mathbb{Z}, \qquad for\ all\ j$$

where c_i and c_j are the net income of cultivation i and dairy herd j, respectively, x_j is the area of cultivation i, y_j is the size of dairy herd j, a_{ki}, and a_{kj} are technical coefficients that capture the level of use of resource k for cultivation i and dairy herd j, respectively, b_k is available resource k, d_{il} is the yield of crop l from cultivation i, e_l is the household self-sufficiency requirement of crop l, f_i is the content of total digestible nutrients (TDN) of residues from cultivation i, and g_i is the TDN requirement of dairy herd j (Koide and Tinga, 2021).

The model analysis was grounded in the actual resource endowments, decision variables, and technical coefficients of the representative farm. Given the farm's constraints in the land, labor, and financial resources, the model was designed to optimize the cropping patterns, feed composition, and herd structure simultaneously, aiming to maximize total net income while ensuring sufficient food and nutrients for both household and livestock needs based on actual productivity levels. The available feedstuffs were integrated into a diet formulation that ensured the dairy cattle's energy balance, with a total digestible nutrient (TDN) content sufficient to maintain productivity, equating to 2,979 kg for a milking cow and 926 kg for a calf. To maintain realistic resource allocation, the model preserved the resources necessary for existing non-farm activities, often overlooked but critical in household modeling (van Wijk et al., 2012).

Three scenarios were developed to assess the impact of dairying using the whole-farm model. In Scenario 1, the baseline household resource allocation was confined to traditional livelihoods, excluding dairy production. Scenario 2 introduced dairy farming, with the herd restructured to meet reproductive conditions. In Scenario 3, raw milk processing was incorporated to enhance product longevity and marketability, allowing for further examination of income improvements through value addition.

3. Results

The dairy performance of the representative farm proved cost-effective, albeit not highly productive (Table 3). Inadequate feeding, limiting the TDN-based energy supply to around 3,000 kg per cow, constrained milk yields. Nonetheless, dairy farming surpassed crop activities in terms of net income and labor efficiency (Table 4). This suggests that expanding the dairy sector could significantly enhance whole-farm economic performance. However, increasing dairy production would necessitate the expansion of cultivated land to supplement TDN content with non-food biomass, varying by crop combination (Table 4). Therefore, the optimal scale and choice of crop activities are crucial. Additionally, restructuring the dairy herd is essential for long-term viability. As with other dairy farms, the representative farm's extended calving interval and high mortality rates pose challenges. To ensure reproductive sustainability, the farm should improve breeding practices, shortening the calving interval to 18 months and maintaining cows in the herd through five lactations (Figure 1). This regenerative herd structure is presumed in Scenarios 2 and 3.

Table 3. Annual dairy performance for the representative farm (2018–2019)

	Yield (L/head)	Net income (MT/head)	Labor (man-hour/head)	TDN[a] (kg/head)
Milking cow	1,620	53,190	359	2,979
Calf	n/a	-500	97	926

[a] TDN content of all feeds supplied by the representative farm.

MT: Metical

Source: Koide and Tinga (2021)

Table 4. Annual crop performance for the representative farm (2018-2019)

	Net income (MT/ha)	Labor (man-hour/ha)	TDN[a] (kg/ha)
Mixed cropping - Cassava, maize, peanut, Napier grass	18,776	498	1,911
Mixed cropping - Cassava, maize, cowpea, peanut	33,369	755	1,977
Mixed cropping - Maize, cowpea, peanut	38,762	1,087	2,490
Mixed cropping - Maize, sweet potato, cowpea, pumpkin	40,925	1,095	2,139
Mixed cropping - Maize, sweet potato, sugar cane, pumpkin	46,950	989	2,471
Mixed cropping - Maize, sugar cane, banana, pumpkin	52,414	820	1,060
Mixed cropping - Sugar cane, banana	27,066	409	118
Mono cropping - Sugar cane	30,283	553	134

[a] TDN content of inedible harvest residues. Edible parts are used for household consumption.

MT: Metical

Source: Koide and Tinga (2021)

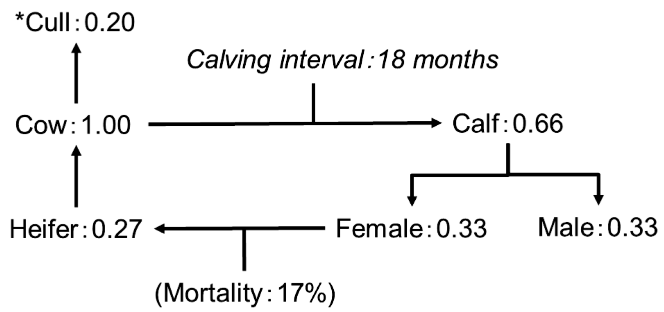

Figure 1. Dairy herd structure used in the model

* It is assumed that a cow remains in the herd through five lactations and that mortality is less than 27%.

Source: Koide and Tinga (2021)

Table 5 presents the outcomes of the model analysis. As the representative farm possesses only one lactating cow, the economic contribution of dairy farming remains limited when compared to its crop and non-farm activities. By reallocating resources used for dairying to cultivation (Scenario 1), the farm could increase net income from cropping by 27% while ensuring food self-sufficiency. However, since this increase is smaller than the current net income from dairying, total net income would decline by 10%. This indicates that the existing suboptimal crop-dairy farming combination is more profitable than an optimized non-dairy (crop-based) approach. Therefore, introducing dairy farming proves more advantageous than merely leveraging existing cropping systems. Nevertheless, the farm must enhance its reproductive efficiency to fully realize the benefits.

According to the model analysis, bridging this gap through a restructured dairy herd and optimized cropping patterns (Scenario 2) would result in a 44% improvement over the farm's current practices while still meeting household food needs and the TDN requirements of the livestock. These additional gains largely stem from dairy farming with a new herd structure comprising three cows. The farm could achieve this structure relatively soon if provided with breeding opportunities, as it currently has a heifer, two heifer calves, and one cow. It is also important to note that Scenario 2 allows for introducing the new herd with minimal alterations to crop activities and net income, compared to Scenario 1. This suggests that establishing a sustainable dairy herd would not require significant tradeoffs with food production or net income from crop activities, thus offering the farm a "pure bonus" from sustainable milk production.

Moreover, an additional benefit could be derived from milk processing. To date, 18% of the raw milk produced by the farm has remained unsold. As a countermeasure, the farm recently began producing yogurt on a trial basis (with support from the Agricultural Research Institute of Mozambique) and discovered that yogurt could be sold at nearly twice the price of raw milk without dead stock. Processing the unsold milk into yogurt, reflected in Scenario 3, increases total net income by 13%. Under these circumstances, dairy farming becomes highly profitable, with the largest portion of its net income (45%) derived from its dairy activities.

Table 5. MIP results in relation to the actual crop/dairy production

	Actual	MIP Scenario 1	MIP Scenario 2	MIP Scenario 3
Cropping				
Mixed cropping - Cassava, maize, peanut, Napier grass	0.23	0	0	0
Mixed cropping - Cassava, maize, cowpea, peanut, pumpkin	0.22	0.24	0.24	0.24
Mixed cropping - Maize, cowpea, peanut	0.33	0.32	0.32	0.32
Mixed cropping - Maize, sweet potato, cowpea, pumpkin	0.32	0	0	0
Mixed cropping - Maize, sweet potato, sugar cane, pumpkin	0.48	0.68	0.70	0.70
Mixed cropping - Maize, sugar cane, banana, pumpkin	0.28	0.90	0.89	0.89
Mixed cropping - Sugar cane, banana	0.11	0	0	0
Mono cropping - Sugar cane	0.17	0	0	0
Dairying (Jersey)				
Cow (head)	1	n/a	3	3
Calf/Heifer (head)	3	n/a	1	1
Net income from cropping (MT)	82,571	104,708	103,422	103,422
Net income from dairying (MT)	53,190	n/a	167,650	223,248
Non-farm income (MT)	171,525	171,525	171,525	171,525
Total net income (MT)	307,466	276,233	442,597	498,195

MT: Metical

Source: Koide and Tinga (2021)

4. Concluding remarks

Dairy production has been extensively promoted among smallholder farms in SSA, playing a critical role in enhancing food expenditure, dietary diversity, and nutritional outcomes. However, effective resource allocation strategies, crucial for optimizing the interaction between dairy and cropping sectors and maximizing overall farm profitability, remain largely underexplored. This chapter investigates such strategies for crop-dairy farms in southern Mozambique based on the findings of Koide and Tinga (2021). Their model analysis demonstrated that, by restructuring the cropping system and dairy herd for sustainable feed and milk production, smallholder farmers could generate significant income from integrated activities while meeting household food requirements and ensuring the energy balance of livestock through efficient use of edible and non-edible farm produce. The results further suggest that farm-based milk processing can substantially increase earnings. Therefore, the comprehensive development of advanced breeding and marketing systems, coupled with effective integration mechanisms with the cropping sector, presents a promising approach to improving the sustainability and profitability of smallholder dairy farming.

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Chapter 5 Facilitation of model application and decision supports to African smallholder farmers

5-1 Feasibility of data collection using farm-based recordkeeping in sub-Saharan Africa

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Abstract

While various methodologies have been proposed to address existing flaws in agricultural surveys, enhancing data accuracy, timeliness, and informativeness remains a significant challenge, particularly within smallholder farming systems. To explore a viable solution, this study examined the feasibility of farm-based recordkeeping, which had previously received minimal attention, through participatory field trials conducted across various African smallholder farming communities. Despite most trial participants being illiterate, most could maintain continuous records, likely due to the adoption of simplified recording formats, meticulous explanations and training for transcribers, and mutual encouragement and assistance among participants. Moreover, through their trial experiences, they discovered diverse benefits of recordkeeping, including facilitating comprehensive farm management reviews and planning for the next season. However, the trial results also highlighted practical challenges, such as limited self-administration and data recording coverage, which were not solely attributable to illiteracy. While advanced digital technologies like smartphones facilitate farm-based recordkeeping, a demand-driven approach that leverages the motivation and retention of recordkeepers is necessary to ensure the autonomous and comprehensive administration of records. Such an approach may include enhancing the functionality of the recording system so that it contributes not only to the collection of quality data but also to farmers' beneficial learning and decision support using the collected data. Continuous interaction between agricultural researchers, extensionists, and farmers through informative analyses of the recorded data and subsequent feedback may also facilitate the widespread adoption of farm recordkeeping.

1. Introduction

Survey flaws negatively impact the accuracy and validity of inferences drawn from data, potentially leading to faulty conclusions and misguided policies. Regarding measurement errors, traditional questionnaire surveys conducted through face-to-face interviews have been contested, as this data collection mode involves several potential error sources, including questionnaire design, interviewer effects, and respondent effects (Groves et al., 2009). Errors from questionnaire design are often associated with the length and complexity of questions, skipping of questions, and the duration of the reference period (Iarossi, 2006). These issues have garnered renewed attention among agricultural economists, who rely on extensive self-reported information from farmers at the plot-crop-season-manager levels to enable multiple analytical strategies (Carletto et al., 2021). The considerable cognitive effort and response time required for highly disaggregated and lengthy interviews may hinder farmers from reporting accurate and consistent information. Furthermore, the long recall periods typically involved in agricultural questionnaires are systematically related to the presence of measurement errors. Wollburg et al. (2020) corroborated this, providing evidence of measurement errors in key agricultural input and output variables, including labor, fertilizer, and harvest quantities. Due to issues with questionnaires and proxy responses, the omission of plots and farm workers frequently occurs, presenting another significant source of bias (Gaddis et al., 2020).

Various approaches have been undertaken to address existing flaws in agricultural surveys, but they often suffer from a tradeoff between survey cost and data quality. Many survey planners have attempted to increase the number of visits within the agricultural season to reduce the length of recall and align visits to key production stages. However, this approach incurs obvious costs, with multiple visits increasing the financial burden and respondent and interviewer fatigue. Empirical evidence indicates that repeated household surveys contribute to lower data quality and biased parameter estimates (Schündeln, 2018; Zwane et al., 2011). Remote sensing is a contemporary approach to enhance data validation at a lower cost, but it presents specific challenges in smallholder production systems, which require high resolution and often feature intercropping patterns that are difficult to characterize based on satellite data (Burke & Lobell, 2017; Rustowicz et al., 2019). Ex-post analysis and bias adjustment are also instrumental. However, economists argue that measurement error and its effects are not necessarily adequately treated and corrected using ex-post econometric tools, highlighting that addressing potential bias ex-ante through appropriate survey design choices may ultimately be a more effective way to tackle the issue (Carletto et al., 2021).

One option that has received less attention but may effectively reduce measurement error and recall bias in agricultural surveys is farm-based recordkeeping. Provided with a simple and distinct recording system that allows farmers to easily and routinely accumulate targeted information, this approach can eliminate significant sources of measurement error resulting from questionnaires, including the length and complexity of questions and long reference periods. Well-designed recording formats facilitate accurate and high-frequency data collection even at the plot-crop-season-manager level. Furthermore, the self-administered nature of recordkeeping prevents data from being affected by the interviewer's ability and relationship with the respondent. The cost of data collection can be significantly reduced, as enumerators would not need to make extended stays with farmers or visit them multiple times. Thus, establishing effective farm-based recording systems may be a promising strategy for maximizing agricultural data quality within budgetary constraints. Nevertheless, farm-based recordkeeping remains largely underrepresented in the literature. Its application is particularly worth considering for sub-Saharan Africa (SSA), where most rural household surveys still involve costly travel and the administration of extensive questionnaires. Understanding whether it is practicable for farmers in this region to adopt recordkeeping as an alternative (or complementary) means for generating a more reliable data set at a lower cost would greatly contribute to agricultural survey research.

This paper aims to provide evidence regarding the feasibility of farm-based recordkeeping in SSA. For this purpose, we conducted participatory trials of farm-based recordkeeping under different regional settings, with various methods of selecting and organizing recordkeepers, and with different types of recordkeeping systems.

2. Materials and methods

2.1. Recording formats

We designed recording formats to enable farmers to document all targeted agricultural information quickly and without requiring special knowledge or skills (Figure 1). In these formats, farmers are supposed to record daily farm operations performed in respective plots, distinguished by cropping systems. In our case, the cropping systems are defined by combinations of crops and cropping patterns (monoculture, intercropping, and mixed cropping). By assisting farmers in measuring the area of each plot using GPS devices and assigning IDs, as in the field trials described later, we facilitate clear identification of the numerous plots they cultivate and simplify the recording of agricultural activities for each plot. This ultimately allows for a comprehensive understanding of key agricultural performance indicators, including yield, profitability, and labor intensity for each cropping system. The recording formats are designed to capture details necessary for calculating these performance indicators, covering the number and hours of family and hired labor utilized for each farm operation, wages paid, types and quantities of farm inputs used, expenditures, and harvest quantities, sales volumes, and prices for each crop. Every farm operation, input, and crop identified through preliminary farmer surveys are incorporated and coded with clear specification, eliminating the need for farmers to write words, reducing recording time, and avoiding the issue of illegible information typical of handwritten records.

Name of the farmily head: ____________ **Plot Number:** ______ **Cultivated area (ha)** ___ m × ___ m (___ ha) **Crop(s):** ____________ **Cropping system:** 1: MONOCROPPING, 2: MIXEDCROPPING, 3: INTERCROPPING

Kind of work: 1: Plowing, 2: Sowing, 3: Hand weeding, 4: Fertilizing, 5: Spray insecticide, 6: Harvesting, 7: Transportation from field to house, 8: Transportation from house to market

Kind of input: 1: Seeds, 2: Organic fertilizer, 3: Chemical fertilizer, 4: Herbicide, 5: Insecticide, 6: Fungicide

Date	Kind of work	Family labor		Employed labor		Input			Tractor service	
		Number of person	Working hour(s)	Number of person	Expenditure (MT)	Kind of input	Quantity (Indicate the unit)	Expenditure (MT)	Area under service (ha)	Expenditure (MT)
/ /										
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Figure 1. An example of a recording format created for farm data collection (paper-based)

2.2. Recording systems

We prepared two contrasting types of media for recording data: traditional paper-based recording systems and newly established smartphone-based recording systems. The traditional paper-based systems involve providing farmers with hard copies of recording forms (and writing instruments as needed) based on the above formats and instructing them on how to record their daily operations. It is desirable to regularly visit farmers to inspect the forms they filled out, offer correction guidance, and collect the completed forms. In contrast, the new smartphone-based recording systems are designed to allow farmers to enter farming information via a smartphone application that implements the same formats. To develop this system, we utilized the Memento Database, a free, flexible database application that allows customization of data entry forms for various purposes, including recording. Memento Database is a powerful, user-friendly tool designed for working with any data, making it possible to store, organize, calculate, and visualize information (MementoDB Inc., 2024). We created data entry forms based on our recording formats in the app (Figure 2). After installing it on their smartphones, farmers can download and use the data entry forms uploaded to the cloud. Since this app supports offline work, farmers can enter data at any time in offline mode once the app is installed and the forms are downloaded. Additionally, we linked the entry forms to spreadsheets in online storage, enabling data synchronization, remote monitoring, and editing (Figure 3). Given the minimal size of data in our formats, free online storage services, including Google Drive, suffice for data uploads, and with minimal internet connection, all records can be synchronized with the spreadsheet instantly with a single click. This beneficial integration of applications and online storage services allowed us to construct smartphone-based farm recording systems that are inexpensive to use.

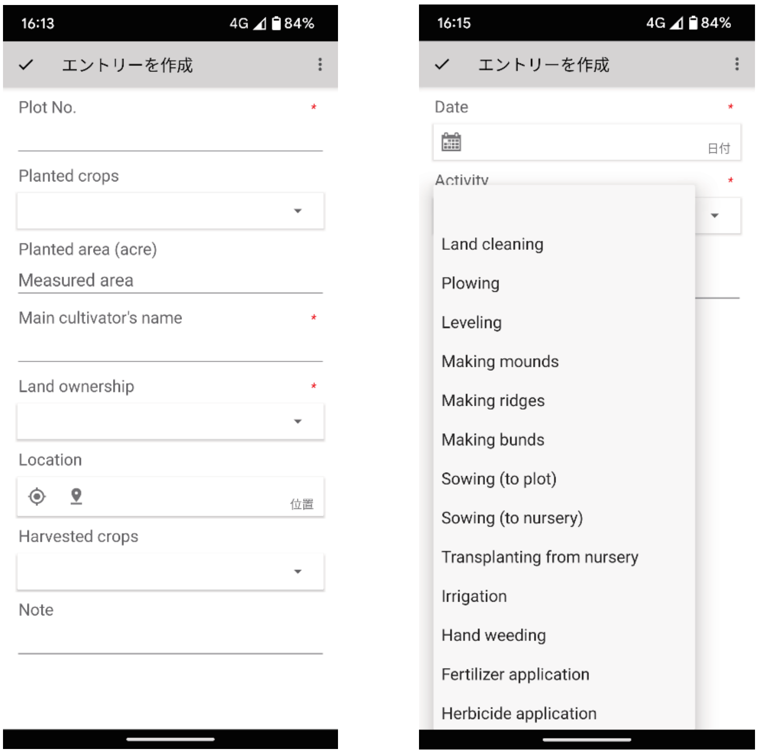

Figure 2. Data entry forms created in the smartphone application (left: for plot registration, right: for recording activities)

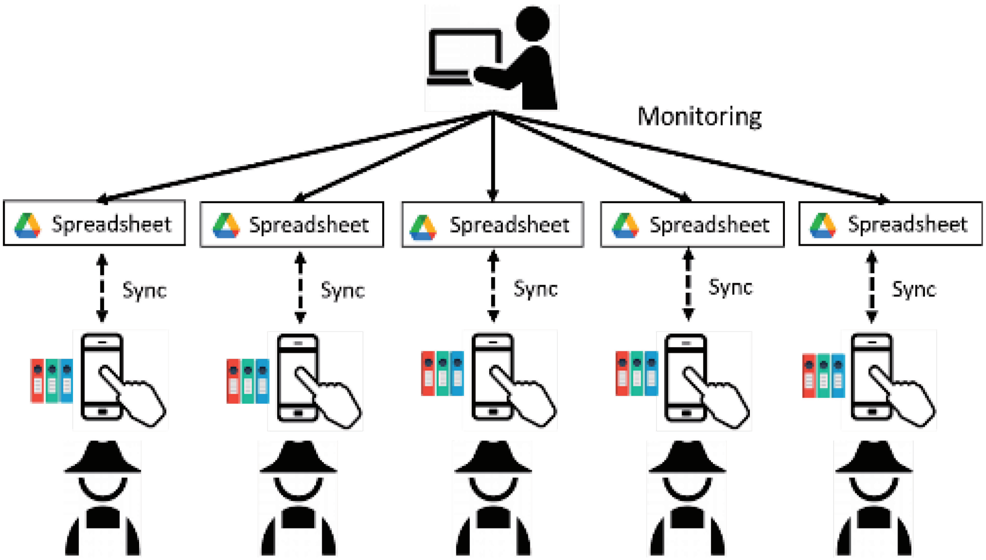

Figure 3. A schematic diagram of smartphone-based farm recording systems

Each recording system has notable advantages and disadvantages. The traditional paper-based recording systems enable even farmers not adept at using devices like smartphones to easily record farming activities; however, they risk record loss due to misplacement or damage. Conversely, the established smartphone-based recording systems, although more challenging for farmers unfamiliar with device operation, offer the advantage of backing up data on the smartphone and online storage, thereby reducing the risk of record loss. Another advantage of this system is the inclusion of data validation functions in the data entry forms, which detect outliers and missing data and condition data approval on their correction. This can significantly reduce recording errors compared to paper-based systems. Furthermore, data uploaded to online storage can be remotely monitored and downloaded, eliminating the need for visiting farmers to inspect and collect record data as required in paper-based systems, thereby substantially lowering long-term operational costs. Although initial costs for purchasing smartphones are necessary for farmers without them, smartphone-based systems generally offer superior convenience and ease of data management compared to paper-based systems. Nevertheless, despite the recent remarkable progress in smartphone usage and internet connectivity in African rural areas, many regions and farmers still lack access to these technologies. Therefore, judiciously utilizing both recording systems based on accessibility is crucial for expanding the application of farming records.

To date, paper-based recording has been used in a few studies pursuing the acquisition and analysis of reliable farm data. However, examples of utilizing such recording for whole-farm modeling, including economic optimization of cropping systems for farmers in SSA, are very limited. As for smartphone-based recording systems, to our knowledge, there are no instances of their practical use for data collection in the field of agricultural economics in SSA. To bridge these gaps, we attempt to demonstrate the opportunities and challenges of farm-based recordkeeping using each recording medium. Considering the varying access to smartphones and the internet across African rural areas, we decided to test the feasibility of paper-based systems in farming communities. We verified the feasibility of smartphone-based systems in regions with sufficient access to smartphones and the internet.

2.3. Recording trials

Between 2013 and 2023, we conducted participatory farm recording trials across several regions in SSA (Table 1). A total of 305 farmers, all smallholders, participated in the trials. The trials were implemented as part of agricultural technology development projects in each region. Thus, the participants practiced farm recordkeeping and implemented on-farm experiments using various agricultural technologies recommended by the projects. We targeted all farmer plots, including those testing these recommended technologies (i.e., experimental plots) and other conventional farming (i.e., non-experimental) plots, for the recording trials. This recording allows evaluating the productivity, profitability, and labor intensity of existing and new cropping systems using recommended technologies. This evaluation, in turn, enables the identification of optimal technology adoption and the expected economic benefits through whole-farm modeling (as detailed in Chapters 2 through 4).

From 2013 to 2022, we employed paper-based recording systems for trials in Mozambique, Ghana, and Burkina Faso. Conversely, in 2023, we adopted smartphone-based recording systems for trials in another region of Ghana, considering the relatively adequate access to smartphones and the internet. In all trials, the methods of selection and grouping of participant farmers were decided by consultations with representatives of target villages, building on existing farmer organizations, traditional authority leadership, or random selection of farmers.

Regardless of the recording system, it is difficult for illiterate farmers to do recordkeeping themselves. This issue was more prevalent among elderly or female household heads but was often mitigated by having children record on their behalf. However, since children could be absent due to schooling, it was important to establish a support system where other farmers could assist. Therefore, in regions where feasible, we leveraged strong social networks led by existing farmer organizations or traditional authorities to select and group record keepers. This was applicable in the trials in Mozambique and Ghana. In contrast, in Burkina Faso, where settlements are more dispersed, grouping farmers was relatively difficult. However, because they have relatively large households and more children who could write, mutual assistance among farmers was less critical, so trial participants were selected randomly in Burkina Faso. Similarly, participants in the Ghana trials were randomly selected for using smartphone-based recording systems, considering remote monitoring and support of data recording, which did not necessarily require direct mutual assistance. However, in all trials, the participating farmers belonged to the same community, and after learning the recording methods together in training sessions, it was agreed that they would assist each other in recording activities as necessary.

To enable continuous recordkeeping by many participating illiterate farmers, the trial focused on enhancing communication between them and their scribes. If the scribe is another farmer, it is uncommon for them to engage in agricultural work together. Even if the scribe is a member of the same household, they might not accompany the participating farmer in their agricultural activities. In essence, no scribe can independently recognize all the tasks the participating farmer performs. Therefore, we encouraged the scribe to interview the illiterate participant at the end of each day to record their activities. Additionally, consensus was reached for illiterate farmers to thoroughly report these activities to their scribe.

At each trial site, we conducted the following participatory activities with the farmers before the trial commenced:

1. Careful explanation of the purpose of farm-based recordkeeping and consensus-building for trial implementation.
2. Selection of proxies and assistants for illiterate farmers.
3. Creation of each farmer’s plot layout, distinguishing and numbering plots based on cropping systems.

4. Training on plot area measurement and methods for weighing inputs and harvests.
5. Confirmation of cropping systems and area measurement in each plot.
6. Explanation and demonstration of data recording methods using each recording system.
7. Learning correct recording methods for various operations and inputs.

Our designated supervisors of recording trials consistently participated in the above activities (Figure 4). These supervisors were selected for their motivation and competence in monitoring and supporting farm recordkeeping at each trial site. They included leaders of farmer groups, village contact persons, agricultural extension agents, and technical staff from local agricultural research institutes. They also regularly monitored the farmers' initiation of recordkeeping activities. Supervisors visited villages in trials employing paper-based recording systems to directly inspect and correct recorded data. In trials using smartphone-based recording systems, supervisors performed these activities remotely by checking data uploaded to online storage and only visited villages when farmers needed direct assistance with operating the smartphone application.

Table 1. Trials of farm-based recordkeeping in the selected African countries

	Mozambique (Nampula, Gurue, Lichinga)	Ghana (Tamale)	Burkina Faso (Saria)	Ghana (Gushie, Kabilpe, Larabanga)
Trial period	2013–2015	2015–2019	2019–2022	2023
Recording systems	Paper-based	Paper-based	Paper-based	Smartphone-based
Recording plots	Experimental and non-experimental plots	Experimental plots	Experimental and non-experimental plots	Experimental and non-experimental plots
Selection of participants	Selected from farmer organization	Selected by village chief	Selected randomly	Selected randomly
Supervisors	Leaders of farmer group	Village contact person and extension agent	Technical staff of research institute	Survey staff (University graduates)
Monitoring	Direct visit	Direct visit	Direct visit	Remote (online)

Figure 4. Recording observations and instructions by an agricultural extension agent in Ghana (left) and technical staff in Burkina Faso (right)

3. Trial results

3.1. Recording performance

Table 2 summarizes the characteristics of participating farmers and their recordkeeping results. In all regions, most participating farmers were male. Despite a high number of illiterate participants, most succeeded in maintaining farming records throughout the trial period. Key factors for this success may include adopting simplified record forms, thorough preparation such as detailed explanations and training on recording methods for recordkeepers, and mutual encouragement and support.

However, the self-administration and data recording coverage were not always adequate. In every region, the number of farmers who independently recorded data was lower than that of literate farmers. This suggests that even literate farmers sometimes had another household member or another farmer keep records on their behalf. In trial sites in Mozambique and Ghana, where the selection and grouping of participating farmers were influenced by existing social networks within farmer organizations or traditional authorities, many farmers had other farmers' record data for them. To encourage this support, leadership was demonstrated by executives of farmer organizations in Mozambique (Figure 5) and traditional chiefs and their aides in Ghana. On the other hand, in trial sites in Burkina Faso and Ghana, where participants were randomly selected, a relatively high number of farmers had other household members, mainly their middle- and high-school-aged sons or daughters, record the data. At the trial site in Ghana, the use of applications for data entry by these youth, who are adept at operating smartphones, significantly contributed to the continuous implementation of farming records (Figure 6).

The coverage of recorded data varied slightly by region. Farmers in Ghana who documented only the activities of experimental plots found the recordkeeping relatively straightforward. Conversely, in other regions where both technical experiment activities and conventional farming practices were recorded, some farmers failed to document activities for all plots. The primary reason was that these farmers cultivated numerous plots in addition to the experimental plots. Even among farmers who succeeded in recording activities for all plots, their records often did not encompass all activities from land preparation to harvest. For these farmers, we needed to provide guidance for adding or correcting data to complete their records.

The characteristics of farm recordkeeping experienced by trial farmers varied significantly across regions. In Burkina Faso, the complexity and difficulty of data recording and management were exacerbated by the large number of plots, crops, and decision-makers involved, particularly within mixed cropping systems. The biophysical context of this situation includes Burkina Faso's location in the Sahel, where limited rainfall and frequent droughts create a heightened need for risk mitigation at the plot and crop levels. Additionally, the social context is defined by traditional extended family living arrangements in rural areas, resulting in more agricultural decision-makers within households than in other regions. Conversely, in Mozambique, nuclear families are predominant in rural households, leading to relatively fewer intrahousehold decision-makers. Ghana occupies a middle ground between Burkina Faso and Mozambique in terms of the number of decision-makers, as rural Ghana is transitioning from extended to nuclear family living arrangements (Koide and Oka 2016). Nevertheless, Mozambique and Ghana, while not as severely impacted as Burkina Faso, continue to face significant production risks such as droughts, making farm recordkeeping challenging for farmers adopting highly diversified and complex cropping systems to address such risks. In Mozambique, this challenge was further compounded by the inadequate leadership of farmer organization executives responsible for monitoring records at certain trial sites and the lack of external support, leading to lower data recording coverage than sites in other countries. Conversely, in Burkina Faso, despite the high difficulty of recording activities, regular record checks and additional guidance by technical staff from research institutes resulted in relatively high data coverage.

Table 2. Characteristics of trial participants and results of their recording activities

	Mozambique (Nampula, Gurue, Lichinga)	Ghana (Tamale)	Burkina Faso (Saria)	Ghana (Gushie, Kabilpe, Larabanga)
Total number of participants	75	120	80	30
Female (%)	30.7	33.3	0	16.7
Literate (%)	46.7	16.7	5.0	20.0
Those who continued recording (%)	84.0	100	95.0	93.3
- Recording process -				
Recorded by him/herself (%)	32.0	16.7	0	9.3
Recorded by a person in the same household (%)	8.0	3.3	95.0	74.7
Recorded by a person in another household (%)	44.0	80.0	0	0.9
- Recording coverage -				
Recorded experimental and non-experimental plots (%)	58.7	n/a	95.0	93.3
Recorded only experimental plots (%)	25.3	100	0	0
Those who discontinued recording (%)	16.0	0	5.0	6.7

Note: During a recording trial spanning multiple cropping seasons, some participants discontinued recording in some seasons and continued recording in the remaining seasons. Therefore, those who continued recording and those who discontinued recording in the table were obtained by counting the number of those who continued and discontinued recording each season, respectively.

Figure 5. A leader of a farmers' organization checks the data recorded by another farmer (Mozambique).

Figure 6. A farmer records data using the smartphone app (Ghana).

3.2. Survey cost

In many trials, a local staff member acted as a supervisor, inspecting the recorded data of approximately ten participants per village. This monitoring represented the primary cost associated with data collection through farm records, and during the first season, when participants were still unfamiliar with recordkeeping practices, it involved around five visits to the participants (once per month). If the supervisor were to collect the same type of data from another ten farmers in the same village through traditional questionnaire surveys, based on our experience, it would take at least five days (two farmers per day), which is comparable to the time required for inspecting recorded data. Since travel expenses, daily allowances, and incentives for farmers are nearly the same between farm record monitoring and questionnaire surveys, the total cost would also be roughly equivalent if the time required for both methods were the same. However, there is a significant gap between the two methods in terms of the timeliness and accuracy of the accumulated data. Furthermore, while questionnaire surveys incur the same costs each season, farm record monitoring becomes progressively less costly as farmers grow accustomed to the practice and recording errors decrease, resulting in fewer necessary staff visits and a marked reduction in total costs, including monitoring. Therefore, the longer the data collection period, the better the relative cost-effectiveness of farm record monitoring is compared to questionnaire surveys. However, this only applies to farmers who can manage the records independently. The social costs of establishing mutual assistance systems for illiterate farmers and introducing smartphone-based recording systems for those without smartphones must be carefully considered, even though ongoing improvements in educational opportunities and economic development in rural areas could mitigate them.

3.3. Farmers' perceptions

Post-trial interviews revealed that participating farmers identified diverse benefits of farming records from their trial experiences, regardless of differences in recording performance. The main advantages cited included easier recall of agricultural inputs and outputs, and proper understanding of the labor and costs required for each farm operation and crop production. Furthermore, they stated that this information aids in comprehensive farm management reviews and planning for the next season. Some farmers emphasized the utility of records in estimating costs necessary to achieve specific yields, determining appropriate timings for critical farm operations such as sowing and fertilizer application, predicting harvest times, and deciding reasonable crop sales prices. Therefore, the recording system introduced serves as an effective tool for collecting quality data for research and a valuable learning tool for farmers to improve their farm management practices.

In the Ghana trial site, where a smartphone-based system was introduced, participating farmers first used a paper-based system with the same recording format before transitioning to smartphone-based recording. This allowed them to compare the convenience of both systems. The results showed that while approximately 10% of farmers reported no significant difference, the remaining 90% said they found the smartphone-based system easier than the paper-based one. Hence, promoting smartphone-based recordkeeping in regions with suitable smartphone usage conditions is promising. However, some trial farmers still exhibited insufficient self-administration and data coverage in their records, highlighting the need for mechanisms to enhance the motivation and retention of farm record keepers.

4. Concluding remarks

This study highlighted the great opportunities for farm-based recordkeeping, which had previously garnered minimal attention, through participatory field trials conducted across various smallholder farming communities, encompassing different recording systems and record-keeper selection methods. Despite most trial participants being illiterate, most could maintain continuous records, likely due to the adoption of simplified recording formats, meticulous explanations and training for transcribers, and mutual encouragement and assistance among participants. The trial results also suggest that farm recordkeeping can facilitate the collection of higher-quality data at a lower cost than traditional questionnaire surveys. Moreover, through their trial experiences, participants identified numerous benefits of recordkeeping, including improved memory, tracking and management of agricultural activities, a clearer understanding of the labor and costs associated with each crop and operation, and facilitating farm management reviews and planning for subsequent seasons.

Our objective in recordkeeping was to facilitate quality data collection from farmers rather than to promote their empowerment; however, our trials ultimately enabled them to become empowered in farm management. This is an outcome that traditional questionnaire-based household surveys, which merely position farmers as "informants," have not achieved. Farmers cooperating with external activities could be categorized as 1) informants, individuals who are interviewed but receive no information or technical support, 2) passive collaborators, those selected or nominated to implement the proposed methods (including farm recordkeeping) without being prepared to provide feedback to the method proponents or themselves, and 3) active collaborators, those prepared to spontaneously offer feedback through activities such as further inquiry, suggestion, review, and planning (Table 3). The administration of questionnaires by external surveyors aids respondent farmers in recalling and verifying their farming practices, such as operation timing, input quantities, and associated costs, offering an opportunity to reexamine their farming practices, which is the initial step of self-learning. In contrast, farm-based recordkeeping allows farmers to independently manage the recall and confirmation of their farming practices. In our trials, some participating farmers merely followed the recording methods as instructed, acquiring new knowledge as the second step of learning from others. Other farmers fully leveraged what they had learned from their recordkeeping experiences to independently review and plan their farm management. They developed the ability to adapt and apply the acquired knowledge to their specific farm conditions and objectives, marking the third step of emerging creativity. Although not clearly observed, sharing new knowledge and experiences with neighboring farmers as the fourth step of mutual learning is highly anticipated, given that our trials were conducted across open farmer fields.

Table 3. Farmers' participation and empowerment levels (hypothetical mapping)

Level of participation / Empowerment level	Informant	Passive collaborator	Active collaborator
(Knowledge sharing)			*
Farm management review/planning			*
Passive learning of new method		*	*
Recall/confirmation of farm management	*	*	*

Source: Authors

Despite the significant potential of farm-based recordkeeping, the trial results also underscored practical challenges, including limited self-administration and data recording coverage, which were not solely due to illiteracy. These challenges made it difficult for us to collect the comprehensive farm management data needed for whole-farm modeling without follow-up activities. While advanced digital technologies such as smartphones, as experienced by trial farmers in Ghana, facilitate farm-based recordkeeping with minimal field support and cost, their use alone appears insufficient to ensure the autonomous and comprehensive administration of records. To address this issue, a technology-driven approach and a demand-driven approach leveraging the motivation and retention of farm recordkeepers are necessary. Given this empowerment of trial farmers, one promising approach is to enhance the functionality of the recording system so that it not only collects high-quality data but also contributes to farmers' learning and decision-making by leveraging the collected data. An example is developing an application capable of formulating improved farming plans using accumulated record data. Such multifunctionality could effectively meet farmers' needs to utilize information from recordkeeping, thereby providing greater incentives to master it. Another example involves local agricultural researchers and extension agents continuously conducting informative analyses using the recorded data, including calculating optimal farm operations and providing ongoing feedback to farmers. This would significantly enhance the interaction between researchers, extension officers, and farmers, thereby encouraging the adoption and dissemination of farm recordkeeping, whether paper-based or smartphone-based. This process could be further accelerated by the accumulation of farmers' beneficial learning and educational support.

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5-2 Application of user-friendly software for the implementation of farm management models in sub-Saharan Africa

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Abstract

Despite the increasing application of mathematical programming models in agricultural research, there is a dearth of user-friendly model-based decision-support tools available for agricultural practitioners, particularly smallholder farmers in developing regions. To address this, we developed efficient software that facilitates the rapid implementation of a mathematical programming model to achieve major objectives of smallholder agriculture, including enhanced income and food security based on diversified crop production. Unlike other expensive and expertise-dependent software, the developed software is freely accessible and open to anyone interested in supporting farmers' decisions, including those without programming expertise. Its easily applicable environment and functions, low data requirements and computational costs, and simple user interface are among its most notable features, enabling widespread application of model-based decision support. Our training experiences with major intended users, including agricultural researchers and extension agents in African countries, have confirmed that the software is highly intuitive and user-friendly, with many users able to grasp the concepts and operate the software to compute optimal solutions. Nonetheless, challenges persist in the operating environment of intended users, such as the glitches associated with older computers predominantly in use. To further promote agricultural decision support using the software, it is recommended to develop complementary tools, including a lightweight smartphone application that enables similar model-based optimization of farm operations, along with handy operation manuals, brochures, and accessible tutorial videos.

1. Introduction

Developing decision-support systems capable of optimizing the allocation of farm resources for smallholder households can provide opportunities to efficiently improve their food security and income. However, utilization of agricultural decision-support systems is generally limited (Collins et al., 2013). This issue may be attributed partly to inadequate system design and convenience. In sub-Saharan Africa (SSA), existing agricultural decision-support systems are primarily designed to optimize specific resource use practices such as fertilizer application (Ouattara et al., 2017; Rurinda et al., 2020; Rware et al., 2020) and irrigation (Nigussie et al., 2020). However, focusing on optimizing specific resource uses can adversely impact other resource uses, potentially hindering the overall improvement in farm performance needed to enhance food security and income. Therefore, optimizing the whole-farm resource allocation is crucial while addressing the tradeoffs between different production activities.

Major applied decision-support models capable of handling the economic optimization of whole-farm management range from single-objective linear programming models to multi-objective goal programming models, fuzzy or stochastic programming models, and more spatially extensive programming models integrating GIS (Mellaku and Sebsibe, 2022). The more sophisticated and integrated the model, the higher the demand for high-precision data, extensive technical skills, and expertise, thus raising the application requirements. Additionally, specialized mathematical programming software capable of executing these models demands high technical skills and expertise, and has a cost burden. Designing simple, accessible, demand-driven farm optimization software is crucial for promoting farmers' decision support. However, such software is exceedingly limited. To the best of our knowledge, there are also very limited agricultural decision-support tools available that are widely usable in rural areas of developing countries, including African farming communities with no or unstable network connection.

Therefore, we developed software that works offline and enables the easy execution of a simple and practical farm management model for smallholder farmers as a new agricultural decision-support tool usable in SSA. This chapter highlights the features of the software and lessons learned from our training experiences with the target users, specifically agricultural researchers and extension agents in different African countries. As such, we clarify the opportunities and challenges of agricultural decision support using the software.

2. Features of BFM series for Africa

We have newly developed multiple software packages called the Builder of Farming Model BFM series for Africa (the "BFM series"). The BFM series was developed by customizing and upgrading the original BFM software (designed to formulate optimal cropping plans in Japan (Oishi 2008) for use in African countries. The series comprises specialized BFMs tailored to the official languages, currencies, cultivated crops of specific African countries, and more generalized BFMs whose users can flexibly modify all these settings. The specialized versions, created as part of agricultural technology development projects implemented in African countries, include an English version for Ghana (BFMgh), a French version for Burkina Faso (BFMbf), and a Portuguese version for Mozambique (BFMmz). The generalized version (BFMen) is an English version that allows for easily modifying area and currency units, farming conditions, and cropping options. All versions possess notable features in the following aspects.

2.1 Easily implementable Excel add-in software

All functions of the BFM series are executed through Microsoft Excel macros, eliminating the need to prepare other calculation tools, such as costly mathematical programming software. This holds a significant advantage in developing regions, including SSA, where potential users may not have the means to purchase or the knowledge to operate such tools. Many agricultural researchers and extension agents in African countries routinely use Microsoft Excel, so there are minimal barriers to starting to use the BFM. Furthermore, the BFM series supports offline work. Therefore, BFMs can be used even in developing countries, including African countries, with insufficient internet connectivity.

2.2 Functionality designed to address farmers' strategies

The BFM series is designed to execute farm management planning models for SSA and to easily identify the optimal combination of crops and the optimal areas to cultivate. The BFM automates a series of processes, from creating linear programming models to executing optimal calculations using those models and outputting calculation results. This contrasts with other mathematical programming software, where numerous codes and formulas must be correctly entered to execute the same processes. With the automation feature of the BFM, users can derive optimal solutions by simply registering information on the farming conditions and management indicators mentioned below (2.3 Data requirement). In contrast to current software designed primarily for developed countries, which optimize farm operations based on monoculture, the BFM series also allows for including various cropping systems, including monocropping, mixed cropping, and intercropping. This allows for farm optimization without compromising the production and market risk hedge through crop diversification, one of African smallholders' most important farm management strategies. Furthermore, the BFM series can incorporate food self-sufficiency requirements based on household dietary preferences. By doing so, the series can compute solutions that enhance the profitability of the entire cropping system and contribute to household food security. These aspects are key livelihood strategies for smallholder farmers in SSA and essential for effective decision support. Additionally, by registering management indexes for cropping options using alternative technologies, the BFM can output solutions showing optimal technology selection and adoption scale. This can assist agricultural extension organizations in devising appropriate dissemination plans for recommended technologies.

2.3 Readily accessible input data

The data that users of the BFM series should input are limited to farming conditions, including the area of agricultural land and leasable area by land-use type, the number of family workers and hired workers, and the number of workable days, and management indicators for each cropping option, including yields, sale prices, costs, and labor requirements. The data that users can optionally input include the types and consumption quantities of staple crops for food self-sufficiency requirements. None of these data requires specialized skills or instruments for acquisition and can be collected through interviews with farmers, though more accurate, high-frequency data collection methods such as farm-based recordkeeping are recommended (as highlighted in Chapter 5-1). Therefore, users can input primary data obtained from farmers into the BFM and immediately perform optimal solution calculations. Data collected in typical farm household surveys in SSA often contain the data required for the BFM; some are publicly available. Therefore, it is also possible to perform optimal solution calculations using this secondary data.

2.4 Availability of sample data

The specialized software packages tailored for respective African countries, including BFMgh, BFMbf, and BFMmz, are accompanied by sample data on typical farming conditions and management practices collected from farmers as part of agricultural research projects conducted by the Japan International Research Center for Agricultural Sciences (JIRCAS) in each country. The sample data included in BFMgh, BFMbf, and BFMmz cover the major local crops project sites in northern Ghana (i.e., maize, pepper, rice, and vegetables), in central Burkina Faso (i.e., sorghum, millet, cowpeas, groundnuts, and rice), and in northern Mozambique (i.e., cassava, maize, pigeon peas, groundnuts, and common beans). The same sample data as BFMgh is available for BFMen. Users in these countries can load their country's sample data and, if necessary, modify and update it to generate optimal cropping plans for local agricultural decision support. Users from other regions can also attempt calculations with the sample data to deepen their understanding of the operational procedures and functions.

2.5 Low cost

Unlike other mathematical programming software, which entails high acquisition costs, the BFM series is free of charge, ensuring accessibility for individuals interested in agricultural decision-support tools but hindered by financial constraints. The BFM series, operation manual, and sample data can be downloaded from the website (JIRCAS, 2024). It can be utilized with basic knowledge of Microsoft Excel, obviating the need for specialized expertise or skills. Additionally, its offline functionality eliminates concerns regarding network connectivity, a common issue in many rural areas of African countries. There are no data acquisition costs when using secondary or sample data. As previously mentioned, the data required from farmers by the BFM series is limited to basic farming information that can be easily collected through simple inquiries. Therefore, even when primary data are used, the acquisition cost is significantly lower than other specialized agricultural decision-support tools that necessitate agronomic and/or environmental variables, which are often challenging and costly for farmers to obtain. Furthermore, the BFM series is characterized by low computational costs, enabling time-efficient model creation, optimal calculations, and output of results. These comprehensive cost advantages significantly lower the financial barriers for users in low-income countries in SSA to utilize agricultural decision-support tools.

2.6 Simple user interface

When the user runs BFM, a startup menu is displayed (Figure 1), and the functionality of BFM is added to Microsoft Excel as an add-in and becomes available for use. The main sheets where users are supposed to read, browse, input, edit, and save are limited to four sheets: the farming condition sheet (fCondition sheet), management index data sheet (iData sheet), index edit sheet (iEdit sheet), and output farming plan sheet (fPlan sheet). The fCondition sheet is designed for easy registration of information on the land to be used, labor force, cost of agricultural machinery and facilities, and types and quantities of crops to be self-sufficient (Figure 2). In BFMen, users can specify the currency and area units to be adopted on this sheet. In the iEdit sheet, designed to register information about cropping options, users can set details such as yield, cost, and labor distribution for each crop (Figure 3). The registered cropping options are automatically listed on the iData sheet (Figure 4). Users can select cropping options they want to include in the optimal calculation and generate the fPlan sheet by clicking a button (Figure 5). The information displayed on the fPlan sheet includes the combination of cropping options to maximize total agricultural income under the set farming conditions, the optimal area of each cropping option, and its maximal income. Users can support decision-making by presenting this information to farmers. Additionally, users can display the specific seed amount required for the optimal cropping areas on the fPlan sheet by registering the sowing rates of cropping options on the iEdit sheet. This information is helpful in proposing cropping solutions to African farmers, especially when measuring the cropping area is not feasible. Users can refer to the detailed operational procedures from the startup of BFM to the output of calculation results in the operation manual (Figure 6). The manual is available in English, French, and Portuguese.

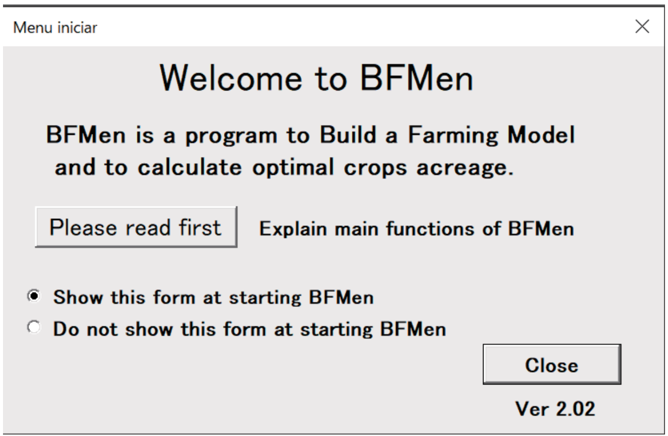

Figure 1. Startup menu of BFMen

[FC Farming condition

	Number of person	Working hour	–
Family labor	5.0 people	8 hour/day	–
	–	–	–
–	–	–	–

	Daily wage	Working hour	Use
Hired labor	12 GHc	8 hour/day	No

Farmland category	Owned land	Rentable land	Rent per ha
1) Lowland	0.5 ha	0.0 ha	0 GHc
2) Upland	1.7 ha	0.5 ha	0 GHc
–	–	–	–
–	–	–	–
–	–	–	–
6) Other	0.0 ha	0.0 ha	20 GHc

Use of rented land	No
–	–
–	–

Fixed cost	0 GHc
1) Machinery	0 GHc
2) Building	0 GHc
3) Others	0 GHc

Number of workable days and hiring days
「Family labor」: Number of per capita workable days
「Hired labor」: Total number of days you can employ (number of days × number of persons)

	Family labor	Hired labor		Family labor	Hired labor
Jan.Bgn	7.0 days	21.0 days	July.Bgn	7.0 days	21.0 days
.Mid	7.0 days	21.0 days	.Mid	7.0 days	21.0 days
.End	7.0 days	21.0 days	.End	7.0 days	21.0 days
Feb.Bgn	7.0 days	21.0 days	Aug.Bgn	7.0 days	21.0 days
.Mid	7.0 days	21.0 days	.Mid	7.0 days	21.0 days
.End	7.0 days	21.0 days	.End	7.0 days	21.0 days
Mar.Bgn	7.0 days	21.0 days	Sept.Bgn	7.0 days	21.0 days
.Mid	7.0 days	21.0 days	.Mid	7.0 days	21.0 days
.End	7.0 days	21.0 days	.End	7.0 days	21.0 days
Apr.Bgn	7.0 days	21.0 days	Oct.Bgn	7.0 days	21.0 days
.Mid	7.0 days	21.0 days	.Mid	7.0 days	21.0 days
.End	7.0 days	21.0 days	.End	7.0 days	21.0 days
May.Bgn	7.0 days	21.0 days	Nov.Bgn	7.0 days	21.0 days
.Mid	7.0 days	21.0 days	.Mid	7.0 days	21.0 days
.End	7.0 days	21.0 days	.End	7.0 days	21.0 days
June.Bgn	7.0 days	21.0 days	Dec.Bgn	7.0 days	21.0 days
.Mid	7.0 days	21.0 days	.Mid	7.0 days	21.0 days
.End	7.0 days	21.0 days	.End	7.0 days	21.0 days

Subsistence crop

Crop	qty(kg)
Maize	1400
Rice	1400

Currency and Area unit

Currency	Area unit
GHc	ha

Figure 2. Example of fCondition sheet (Sample data for Ghana are loaded on BFMen.)

[El]

Summary of farming indexes

No.	1
Area	Tamale
Crop	Maize
Cropping system, Variety, etc.	

Gross income/ha (Ghc, kg)	
Yield	1,485
Unit price	1
Other incomes	
Total	1,351
Variable cost/ha (Ghc)	
Cost of seeds	10
Cost of fertilizer	515
Cost of agrichemicals	43
Cost of energy and power	
Cost of other materials	
Land improvement and water use	
Rental cost	
Transportation charge	
Other costs	162
Total	730
Quantity of seeds (kg/ha)	28.1
Proportional profit (Profit coefficient)	621

Working hour/ha

Jan.Early		July.Early	56.1
.Mid		.Mid	60.7
.Late		.Late	46.7
Feb.Early		Aug.Early	23.2
.Mid		.Mid	14.8
.Late		.Late	13.5
Mar.Early		Sept.Early	11.1
.Mid		.Mid	10.2
.Late		.Late	17.1
Apr.Early		Oct.Early	39.8
.Mid		.Mid	52.1
.Late	0.5	.Late	39.5
May.Early	12.9	Nov.Early	15.9
.Mid	19.2	.Mid	10.3
.Late	25.2	.Late	9.8
June.Early	36.6	Dec.Early	11.7
.Mid	46.1	.Mid	11.1
.Late	48.0	.Late	7.4

Land use

Land category	Upland	
-		
Cultivation/Begin	April	Late
Cultivation/End	December	Late
Lowest limit of cultiv		
Upper limit of cultiva		

Figure 3. Example of an iEdit sheet (Sample data for Ghana are loaded on BFMen.)

	A	B	C	D	E	F	G	H	I	J	K	L
1	[MI											
2		No.	Area	Crop	Cropping system	Scale of investigation	Variety	Yield	Unit price	Gross income	Cost of seeds	Cost of fertilizer
3	☑	1	Tamale	Maize				1485	0.91	1351.35	10	515
4	☑	2	Tamale	Pepper				1687	4.59	7743.33	70	2782
5	☑	3	Tamale	Rice	Rainfed			3122	1.1	3434.2	172	1353
6	☑	4	Tamale	Rice	Supplementary irrigation			3842	1.1	4226.2	234	554
7	☑	5	Tamale	Leafy veget	Dry season			1012	8.3	8399.6	2725	682

Figure 4. Example of an iData sheet (Sample data for Ghana are loaded on BFMen.)

	A	B	C	D	E	F	G	H	I	J	K
1	[Farming plan]	[Memo space] This table is an optimal plan which is calculated using the data of sheet"fCondition" and sheet"iData". You can get the new plan by modifying the numerical values (crop acreage, income, cost etc.) in the cream-colored cells.									
2	Copy										
3	Detail of Plan										
4											
5											
6			whole management	Maize	Pepper	Rice Rainfed	Rice Supplementary irrigation	Leafy vegetables Dry season		Rented land acreage Part time days	Land rent Part time Unit price
7		Crop acreage (unit: ha)	2.70 ha								
8		Lowland (ha)	1.00 ha	–	–	0.11	0.40	0.50		0.00 ha	0 GHc
9		Upland (ha)	1.70 ha	0.94	0.76	–	–	–		0.00 ha	0 GHc
15		Quantity of seeds(kg/ha)									
16		Maize		26.5	–	–	–	–			
17		Pepper		–	3.6	–	–	–			
18		Rice		–	–	19.4	92.4	–			
19		Leafy vegetables		–	–	–	–	2.4			
35		Total gross income (GHc)	13,366 GHc	1,274	5,862	361	1,669	4,200			
36		Total variable cost (GHc)	5,971 GHc	688	2,428	226	474	2,155			
37		Proportional profit (GHc)	7,395 GHc	586	3,434	135	1,196	2,045			
38		Fixed costs(depreciation etc.) (GHc)	0 GHc								
39		Land rent (GHc)	0 GHc								
41		Hired labor cost (GHc)	0 GHc							0.0 day	12 GHc
42		Agricultural income (GHc)	7,395 GHc								

Figure 5. Example of fPlan sheet (Calculated using sample data for Ghana on BFMen.)

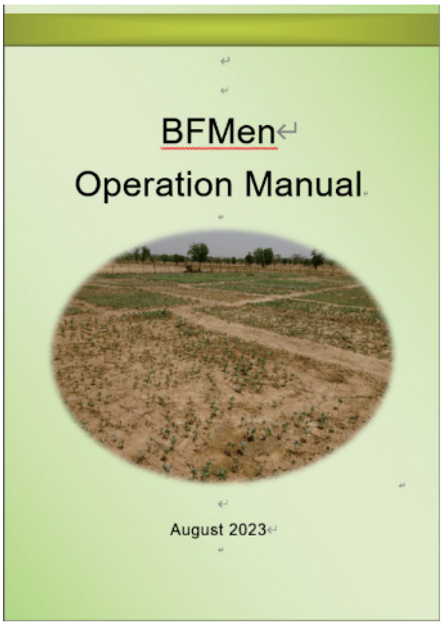

Figure 6. Operation manual of BFMen

3. Local needs and challenges of the BFM series identified through training sessions

The BFM series aims to support farmers' decision-making. However, many farmers in SSA lack the knowledge to operate both computers and Excel. Therefore, we promoted knowledge sharing with the local extension agents responsible for providing agricultural guidance to farmers through training sessions on using the BFM series, assuming that they would be the primary intended users. Training sessions were conducted for approximately 120 agricultural extension agents and their technical advisors from various African countries, including Ghana, Burkina Faso, Nigeria, Mali, Ethiopia, Uganda, and Mozambique. Next, we use the training sessions we conducted with agricultural researchers and extension agents in northern Mozambique and the local technical staff of the Sasakawa Africa Association (SAA) to highlight the opportunities and challenges of the BFM series from the perspective of the trainees' evaluation and proficiency.

In northern Mozambique, we initially instructed researchers in agricultural economics at the Mozambique Agricultural Research Institute (IIAM), who are mainly responsible for training agricultural extension agents on utilizing BFMmz. These researchers effortlessly mastered the operation of BFMmz and successfully calculated optimal cropping solutions using available regional statistics on the necessary inputs and outputs for various cropping practices (Figure 7). Additionally, we provided training on BFMmz to IIAM researchers from other fields, including agronomists, and discovered that some participants subsequently used it for analyses, such as evaluating the impact of introducing new crops. This implies that the BFM series holds potential applications not only for agricultural economists but also for agronomists.

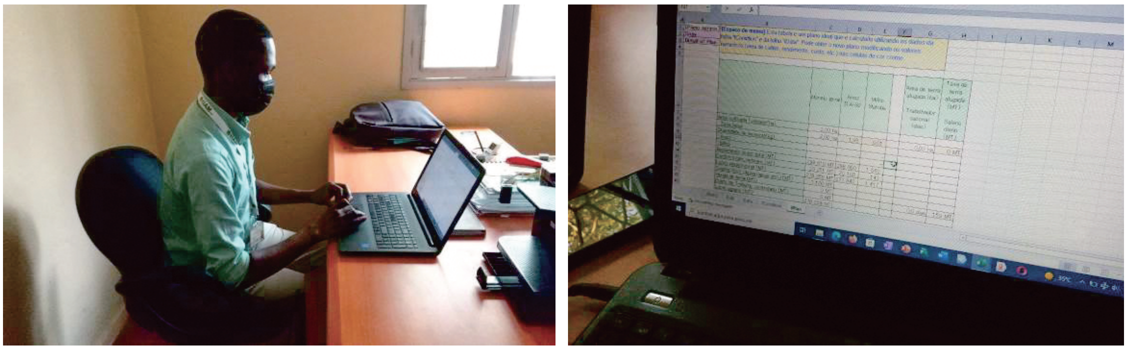

Figure 7. Calculation of optimal cropping solutions using BFMmz by an agricultural economist (left) and the output screen (right)

Agricultural economists at IIAM conducted BFMmz training sessions for agricultural extension agents across multiple regions. The trainees engaged in hands-on learning by operating BFMmz on their own computers and adhering to the operational procedures from input to output, as demonstrated by the instructors. Even though most trainees were unfamiliar with agricultural economics, they were engrossed in BFMmz. They were passionate about simulating how the optimal cropping solutions change when altering farming conditions such as the cultivation area, labor force, and employment, and were diligently exploring ways to efficiently improve total agricultural income (Figure 8). Although BFMmz is intended as a support tool for those who receive cropping solutions (i.e., farmers), it was confirmed that it also serves as a learning tool for those who provide cropping solutions (i.e., researchers and extension agents). In addition, we paired the participants into groups of two, with one acting as a farmer and the other as an extension agent. The extension agent's role was to extract farming information from the farmer role and create optimal cropping plans, then present them to the farmer role, engaging in role-playing learning. As many trainees were extension agents who also engaged in farming themselves, they provided accurate farming information to the extension agent role, identifying the optimal cropping solutions. As a result, they seemed to realize the usefulness of BFMmz even more.

Figure 8. Creation of optimal cropping plans by agricultural extension agents at the training session

We also provided training on the BFM series to the local technical staff of SAA, who are engaged in technical guidance of agricultural extension agents in Nigeria, Mali, Ethiopia, and Uganda. We explained the basic operation of the BFM series and how to use the BFM series to identify the optimal technology adoption for improving the benefits to farmers using regenerative agricultural technologies, which the technical staff was focusing on. For example, based on the on-farm trial results of cultivation techniques such as intercropping between cereals and legumes, and the integrated use of chemical fertilizers and compost, we showed the trainees how to calculate the desired combinations and scale of adopting these techniques among existing cropping options using the BFM series, along with their expected benefits. Many trainees showed a keen interest in using the BFM series, and after training, they decided to collect data from farmers they were supporting and attempt to identify the optimal cropping and technology adoption of regenerative agriculture.

Through the training sessions for target users from various African countries, we confirmed that most trainees could understand and master the concepts, operational methods, and specific applications of the BFM series after a few hours of training, indicating that the BFM series is simple and user-friendly. However, some trainees did not own a computer and had to borrow one, while others who owned a computer used old ones with slow or unstable Excel macros. Such challenges in the operating environment could substantially constrain increasing the use of the BFM series in SSA. In addition, in the rural areas of SSA, where agricultural extension agents are scattered for farmer guidance over a wide area, ensuring the means for initial trainees to convey the methods of using the BFM series to potential users in other regions would also be an important challenge.

4. Concluding remarks

Very limited agricultural decision-support tools are available for smallholder farmers in developing regions such as SSA. To our knowledge, there is no easy-to-use decision-support software that fully considers the key livelihood strategies of smallholder farmers, including the pursuit of food security, risk management, and income improvement. The BFM series can serve as such software, allowing for implementing a farm management model that explicitly integrates these key livelihood strategies. Unlike costly and expertise-based mathematical programming software whose main users are limited to researchers and experts in operations research, the BFM series is free and open to anyone who seeks to support farmers' decisions, including those without programming expertise. The easily applicable environment and functions, low data requirement and cost, and simple user interface are among the most prominent features, enabling extended application of model-based decision support. Our training experience in using the BFM series for agricultural researchers and extension agents in African countries has confirmed that the BFM series is virtually uncomplicated and user-friendly, with many users able to understand the concepts and handle operations to compute optimal cropping solutions under different conditions. However, there remain challenges in the operating environment among intended users, including the glitches of many older computers in use.

Considering the ease with which African users comprehend the BFM series and the challenges their usage environments present, two advanced utilization strategies for the BFM series appear promising. The first strategy entails expanding the application of the BFM series to other developing regions, including Southeast Asia, where research and extension personnel and computer usage environments are relatively more prevalent. Although the BFM series is tailored for smallholder farming in SSA, a generalized version such as BFMen could be effectively deployed to support decision-making in numerous other developing countries where smallholder farming predominates, either directly or with additional modifications. In Southeast Asia, where integrated farming systems involving diverse production sectors are common among smallholders, fostering the development and application of such software through collaboration with researchers and extension workers in these regions would be highly advantageous.

The second strategy is to upgrade the BFM series to a more adaptable and user-oriented decision-support tool by, for instance, developing a lightweight smartphone application that enables similar mathematical model-based optimization of cropping systems. The release of such a smartphone application could lead to more widespread decision support, given the increasing number of smartphone users in developing countries, including African and Asian nations. In order to communicate the use of the BFM series to more potential users, it is also important to promote time- and cost-efficient training methods (e.g., using ICT tools) as an alternative to direct face-to-face training. In addition to the operation manuals, handy brochures highlighting the features of the BFM series and accessible tutorial videos demonstrating the operation procedures would also contribute to further promoting the use of the BFM series.

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5-3 Farmers' evaluation and outcomes of decision support using a farm management model: Case of northern Mozambique

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Abstract

Agricultural decision support based on mathematical programming models can elucidate pathways to improved livelihoods for resource-constrained farmers by, for instance, identifying alternative cropping strategies that efficiently use scarce resources. However, the perceived value of these cropping strategies by farmers and their actual impact on livelihoods remain largely unexplored. Through participatory on-farm experimentation of bespoke cropping solutions derived from a farm management model in northern Mozambique, this paper investigates the real-world outcomes of model-based agricultural decision support and evaluations by local farmers. The findings revealed that many farmers recognized the advantages of the recommended cropping strategies, as these enhanced their production planning through optimal crop selection and management according to their resource availability and performance, thereby enabling substantial income gains. Moreover, these income gains allowed farmers to meet various livelihood needs and objectives, including improved housing, agricultural reinvestment, non-agricultural enterprises, and healthcare. However, some farmers encountered difficulties in fully utilizing the cropping strategies or even rejected them. Given the practical challenges identified by farmers and the reasons for rejection, it is imperative to facilitate the adoption of these prepared cropping solutions by improving their accessibility, timeliness, interpretability, and usability.

1. Introduction

Mathematical programming model-based decision support for the efficient allocation of limited resources across multiple farm production enterprises can elucidate pathways to improved food security and income for smallholder farmers in sub-Saharan Africa (SSA). Specifically, decision-support models with reduced technical and computational demands can leverage typical agricultural household survey data to generate promising cropping alternatives for a wide range of farmers (Koide et al., 2018). However, the practical adoption of these decision-support models by farmers remains limited (Collins et al., 2013). Thus, increased efforts are required to bridge the persistent gap between models and end-users (Mössinger et al., 2022).

Current model-based cropping decision-support research, despite its robust analytical frameworks, sophisticated modeling techniques, and insightful findings, is typically restricted to computer-based simulations of optimal crop mixes as alternatives to conventional practices (e.g., Mohamad and Said, 2011; Felix et al., 2013; Otoo et al., 2015; Buzuzi and Buzuzi, 2018). The perceived utility of these proposed cropping alternatives by farmers, their actual adoption, and the subsequent impact on targeted outcomes are rarely explored. Only a few case studies have tested the provision of cropping solutions derived from these models to farmers and examined whether they effectively supported decision-making (e.g., McCarl, 1977; Mössinger et al., 2022). To our knowledge, no studies have empirically measured farmers' benefits from model-based decision support through experimental investigations involving baseline and endline surveys. It is imperative to conduct impact evaluations of agricultural decision-support tools based on well-structured field experiments. Such evaluations could provide crucial evidence-based recommendations for farmers and policymakers, promoting the adoption and utilization of these tools.

This paper, focusing on the field application of the African Smallholder Farm Management Model (ASFAM) presented in Chapter 1-2, seeks to elucidate farmers' evaluations of model-based, tailor-made agricultural decision support and its impact on agricultural and livelihood outcomes.

2. Materials and methods

To empirically demonstrate the impact of agricultural decision support provided to individual farm households through ASFAM, we conducted randomized controlled field experiments in the Nacala Corridor of northern Mozambique, an area characterized by a high concentration of smallholder farmers and located within the Southern African Growth Belt, where agricultural development has significantly accelerated in recent years. During the 2015–2016 cropping season, we conducted a comprehensive baseline survey of 260 smallholder households, consisting of treatment (n=130) and control (n=130) groups randomly selected from 12 villages in the Nacala Corridor area. The survey combined a structured questionnaire to collect detailed data on available farm resources, agronomic and economic performance of various cropping systems, and non-farm activities from individual households, with direct measurements of crop areas and yields from every plot cultivated by each household. The baseline survey results showed no statistically significant differences in household characteristics and outcome variables between the treatment and control groups. Based on this, we implemented interventions for the treatment group before the 2016–2017 cropping season. Using the collected baseline data and ASFAM, we calculated the optimal cropping solutions for each treated household and provided them with handouts presenting the optimal solutions, thereby delivering model-based decision support (Figure 1). During this decision support, we carefully explained to each treated household that the cropping solutions are tailor-made and designed to maximize total agricultural income based on their farming conditions, performance, and dietary preferences. Adopting the solutions was voluntary. We also illustrated the field layouts to each household to help them understand the cropping solutions.

After the 2016–2017 cropping season, we conducted an exhaustive endline survey for the treatment and control groups. The survey included the same comprehensive direct measurements of all plots and crop yields as in the baseline survey to accurately assess target outcomes, including total agricultural income. Additionally, we conducted a structured questionnaire survey with the treatment group regarding their final decision to adopt the cropping solutions, their perceived utility of the solutions, and reasons for their choices. Furthermore, in 2022, five years after the endline survey, we conducted a follow-up survey with the households that had adopted cropping solutions in one of the 12 villages. Those who still resided in the village as of the survey (two households) were interviewed about their household expenses realized after the endline survey. This survey aimed to highlight improved household livelihoods resulting from the outcomes of our decision support.

Figure 1. Explanation of the cropping solution to a treated farmer

3. Results

3.1 Farmers' evaluation of model-based decision supports

The endline survey revealed that 46% of households in the treatment group adopted the provided cropping solutions, and 60% of them adopted the optimal crop composition suggested by the cropping solutions, while the remaining 40% adopted both the optimal crop composition and the recommended cropping area. These findings illustrate the practical challenges farmers face in fully adopting cropping solutions. Nevertheless, 71.9% of households that adopted the cropping solutions reported an increase in total agricultural income compared to the previous cropping season, with only 21.1% reporting no significant change and 7.0% reporting a decrease (Table 1). Notably, all households that reported an increase in agricultural income attributed this improvement primarily to adopting cropping solutions.

In contrast, only 20.9% reported an increase in total agricultural income among households that did not adopt the cropping solutions, 46.3% reported no significant change, and 31.3% reported a decrease (Table 1). The positive evaluation of the cropping solutions indicates that model-based decision support met the farmers' expectations for achieving desired outcomes. The primary advantages of the cropping solutions, as identified by adopting households, included improved production planning and management based on appropriate crop selection, leading to increased production of essential food crops and a substantial rise in total income.

Among the households that did not adopt the cropping solutions (54%), 38% cited reasons such as insufficient understanding of the solutions (31.9%), lack of labor (27.7%), and lack of inputs (14.9%) for their rejection (Table 2). These responses suggest that a single explanation of the cropping solution may not have been sufficient for complete understanding and that some households may have been significantly concerned about the shortage of labor and inputs required for transitioning to the proposed cropping systems. The remaining 16% of non-adopting households did not receive the cropping solutions or their instructions due to absence during the intervention. These results indicate the necessity of providing more accessible, timely, interpretable, and usable cropping solutions to enhance their adoption by farmers. Meanwhile, some households that adopted the cropping solutions identified key difficulties, such as the need for labor employment (24.6%), purchase of inputs (7.0%), and technical issues (7.0%), although 56.1% reported no difficulties (Table 3). Although the proposed cropping solutions were designed to meet labor, input, and technical requirements, it appears that some farmers struggled to adequately plan for and fulfill these requirements during implementation. These findings suggest that enhanced managerial and technical assistance could promote broader adoption of cropping solutions.

Table 1. Farmers' perception of the achieved income level compared to the previous season (n=130)

	Adopted	Not adopted
Increased (%)	71.9	20.9
Almost same (%)	21.1	46.3
Decreased (%)	7.0	31.3

Table 2. Reasons for rejection of the proposed cropping solution (n=50), multiple answers allowed

Lack of understanding (%)	31.9
Lack of labor (%)	27.7
Lack of inputs (%)	14.9
Health problems (%)	14.9
Lack of technical follow-up (%)	6.4
Lack of favorable rainfall (%)	6.4
Others (%)	14.9

Table 3. Difficulties in adopting the proposed cropping solution (n=60), multiple answers allowed

No difficulty (%)	56.1
Hiring labor (%)	24.6
Purchasing inputs (%)	7.0
Technical support (%)	7.0
Others (%)	8.8

3.2 Actual outcomes of model-based decision support

Although less than half of the households in the treatment group adopted the cropping solutions, the endline survey revealed that the treatment group achieved, on average, a total agricultural income approximately 1.5 times higher than that of the control group. This result indicates that model-based decision support significantly contributes to the income improvement of smallholder households despite the aforementioned practical challenges. Notably, the total agricultural income of households that adopted the cropping solutions was approximately double that of households that rejected the solutions and the controlled households (Figure 2). This fact demonstrates that adopting cropping solutions substantially enhances the livelihoods of smallholder households. Corroborating this evidence, we confirmed through a follow-up survey that households adopting cropping solutions have achieved diverse livelihood needs and goals owing to increased income. Specifically, they have realized home renovations (Figure 3), the purchase of furniture and motorcycles, the introduction of new crops, the increase of livestock, the initiation of manufacturing and retail businesses (Figure 4), the purchase of medicines, and hospital visits. A farmer documented these household expenditures realized by adopting cropping solutions in a notebook (Figure 5). These accomplishments demonstrate that the economic impact of model-based decision support significantly enhances the quality of life and satisfaction of smallholder households by improving living conditions, agricultural reinvestment, non-farm employment, and healthcare. Furthermore, we observed instances where farmers who achieved increased income by following the cropping solutions instructed relatives in other villages about crop selections, resulting in similar income improvements for those households. This indicates that the impact of model-based decision support can be disseminated through farmer-to-farmer extension.

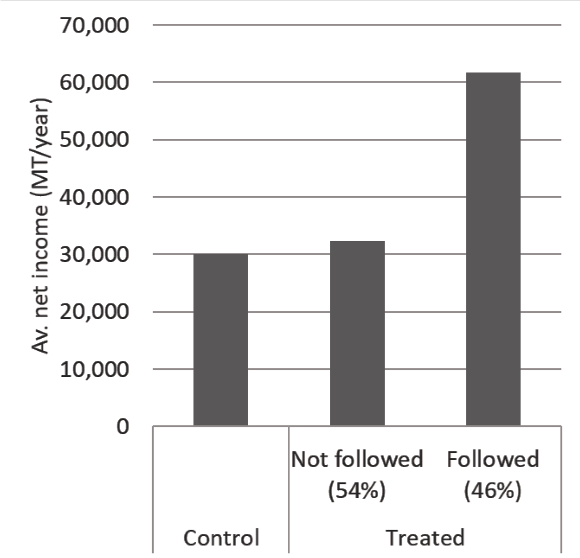

Figure 2. Agricultural net income levels between control and treated households

Figure 3. A farmer's house renovated using increased income from the proposed cropping solution

Figure 4. A sewing machine purchased to start a business by a farmer using increased income from the proposed cropping solution

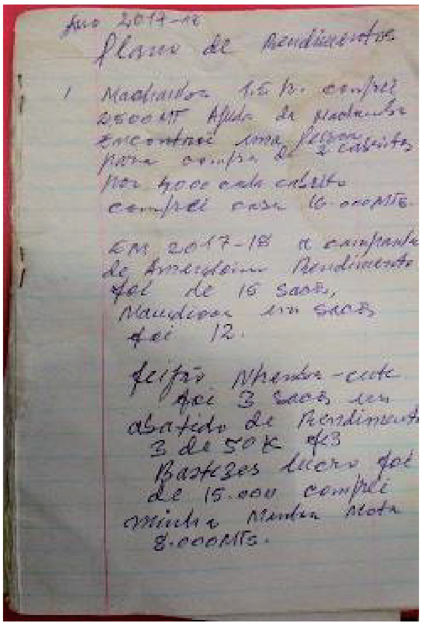

Figure 5. A notebook documenting expenditures made by increased income from the proposed cropping solution (recorded by a farmer, including purchases of a bike, goats, and vegetable seeds)

4. Concluding remarks

Tailor-made agricultural decision support, facilitated by ASFAM, enabled smallholder households in northern Mozambique to significantly enhance their production planning through optimal crop selection and management, resulting in substantial increases in food production and income. All households that adopted the alternative cropping strategies reported these tangible benefits positively. Moreover, the notable rise in household income permitted them to meet various livelihood needs and objectives, including improved housing, agricultural reinvestment, non-farm enterprises, and enhanced healthcare. However, some farmers faced difficulties in fully utilizing the cropping solutions or even rejected them. Given the practical challenges identified by farmers and the reasons for rejection, future efforts should concentrate on promoting the widespread adoption of these cropping solutions by improving their accessibility, timeliness, interpretability, and usability. These enhancements could be partially achieved by developing and distributing representative cropping solutions tailored to specific regions or household categories as alternatives to or complements of existing tailor-made cropping solutions. Regardless of the solution farmers adopt, providing managerial and technical support will facilitate their continuous whole-farm management reviews and planning. Further empirical research is essential to better understand adoption dynamics and inform policy.

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Application of farm management models for decision support to smallholder farmers in Sub-Saharan Africa

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