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).

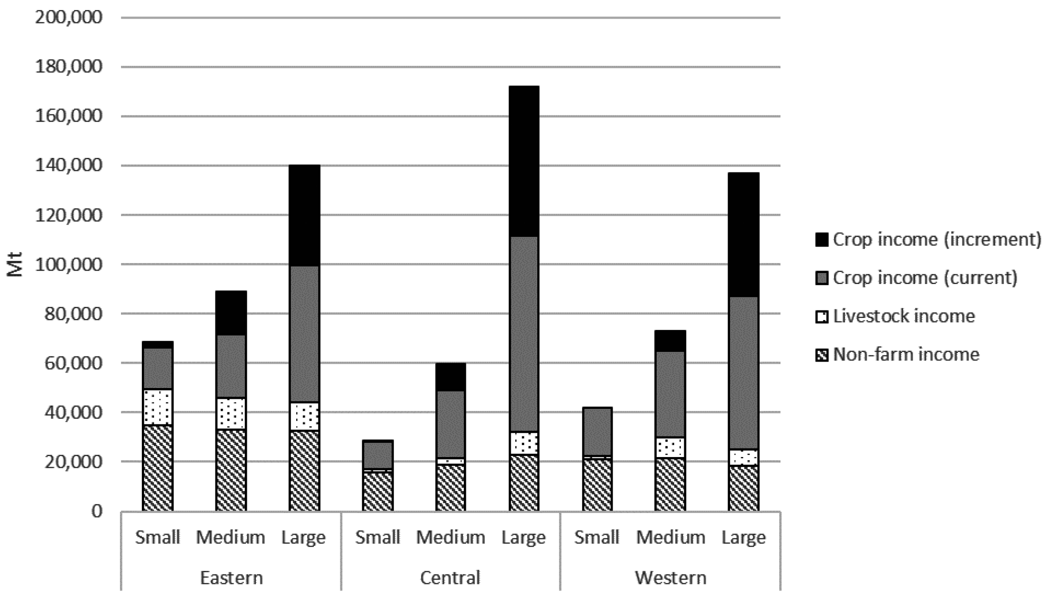

Fig. 1. Increase in household income by introducing the cropping solutions

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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