MALAWI

IFPRI

STRATEGY SUPPORT PROGRAM | REPORT

OCTOBER 2024

Does Location Matter? A Spatial Analysis of the Factors Influencing Adoption of Cereal-Legume Intercropping among Smallholder Farming Households in Malawi

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ACRONYMS

AEZ	Agroecological zone
CMAP	Central Mid-altitude Plateau zone
CSL	Central and Southern Lakeshore zone
DeSIRA	Development of Smart Innovations through Research in Agriculture project
FAO	Food and Agriculture Organization of the United Nations
IFPRI	International Food Policy Research Institute
IHS	Integrated Household Surveys
IITA	International Institute of Tropical Agriculture
LSV	Lower Shire Valley zone
MK	Malawi Kwacha
NL	Northern Lakeshore zone
NMAP	Northern Mid-altitude Plateau zone
PHL	Post-harvest loss
SMAP	Southern Mid-altitude Plateau zone

EXECUTIVE SUMMARY

This study examines the adoption of sustainable agricultural intensification practices—particularly cereal-legume intercropping—by smallholder farming households in Malawi. The focus of the study is on how spatial variation in key factors related to agricultural production and marketing influences farming households' decision-making processes under risk. Separate analyses are done for six distinct agroecological zones in Malawi to evaluate how resource and market constraints affect farming households' decisions to employ intercropping practices on their cropland and how the variations in these constraints have differing impacts on adoption of intercropping across different regions. This study provides valuable insights into the complexities of smallholder farming choices in diverse geographic contexts.

Overlooking spatial variations in modeling the adoption of sustainable agricultural intensification practices by smallholder farming households may lead to inaccurate results and recommendations. This is because different regions or agroecological zones in Malawi exhibit significant differences in temperature, rainfall patterns, soil types, market access, and population density. These factors affect crop suitability and labor-land dynamics, making it essential to consider location-specific conditions in analyzing farming households' production choices under risk. This study, therefore, addresses two critical research questions raised by the distinct spatial variations across regions in Malawi:

- Does location matter when modeling smallholder farming households' adoption decisions?
- Does considering crop suitability and adaptability strengthen our understanding of cereal-legume intercropping adoption patterns across different regions?

To address these questions, we considered altitude, temperature, rainfall patterns, and seasonality across the districts of Malawi to classify the country into six agroecological zones (AEZ): the Northern Mid-altitude Plateau (NMAP), the Northern Lakeshore (NL), the Central Mid-altitude Plateau (CMAP), the Central and Southern Lakeshore (CSL), the Southern Mid-altitude Plateau (SMAP), and the Lower Shire Valley (LSV). Using dynamic stochastic programming methods, the analysis assesses for each AEZ the impact of varying degrees of access to land, labor, input markets, and output markets on farming households' decision-making processes around the cropping systems they employ.

The results show that accounting for spatial variation in such factors is crucial to more clearly understanding patterns of adoption of sustainable agricultural intensification practices by smallholder farming households, as diverse behaviors are revealed across different zones. Our analysis suggests that out of the different constraints that farming households face across regions, land and market access mattered the most in the farming households' decision process.

The study highlights the significance of land constraints across all regions, but with the SMAP zone being the most land-constrained. The introduction of a land policy (scenario 3) influences farming households in SMAP to intercrop more compared to farming households in other zones, likely due to the more binding land constraint within the zone. Land constraints affect the optimal production plans and cropping system choices of farming households in SMAP. The study underscores the importance of considering the influence of land constraints when designing agricultural interventions aimed at supporting sustainable farming practices.

The study also highlights that access to agricultural markets shapes decisions by smallholder farming households to adopt cereal-legume intercropping systems across all AEZs. However, the study highlights how access to input markets matters the most in the NL zone, where it is seen that increasing access to input markets for legumes (scenario 4) results in farming households deciding to integrate legumes into their cropping systems. The level of legume integration in the cropping systems of smallholder farming households varies across zones depending on various location-specific factors—for smallholders in the NL zone, improved access to legume input markets will substantially increase their adoption of legume-based cropping patterns.

More broadly, the study underscores the importance of context-specific approaches in shaping farming households' adoption of sustainable agricultural intensification practices. The adoption of cereal-legume intercropping systems varies across different agroecological zones. Future initiatives aimed at promoting the use of sustainable agricultural intensification by smallholder farming households should tailor any interventions so that they most appropriately address the unique challenges and opportunities present in different agroecological zones. Accounting for such spatial variability in designing such efforts will result in increased adoption of sustainable and contextually relevant farming practices.

In addition, this study highlights the role of resource and market constraints in determining whether farming households adopt sustainable agricultural intensification practices, particularly constraints on land and access to input markets. Future sustainable agricultural intensification promotion efforts should prioritize interventions targeted at addressing land and market constraints. Suitable interventions include promoting sustainable land management strategies, programs to improve access to agricultural input and output markets, and providing support to farming households as they adopt innovative and sustainable farming techniques that align with their cropping system preferences and enable them to overcome many of the agricultural production and marketing constraints observed in the different agroecological zones.

The results of this spatial analysis offer a valuable resource for policymakers, agricultural practitioners, and researchers by providing some actionable insights for developing targeted interventions and strategies to support sustainable agricultural practices in Malawi. By recognizing the diverse adoption patterns of smallholder farming households and the influence of location-specific constraints on their farming practices, stakeholders can design contextually relevant initiatives to enhance smallholder farming households' resilience and productivity. Among the key policy recommendations from the study are undertaking interventions to improve access to agricultural inputs, such as legume seeds, and formulating and implementing strategies to enhance farming households' access to markets in which to sell their produce. Components of such interventions might include establishing a timely market information system for both farming households and buyers of their produce, providing farming households with contingent lines of credit for obtaining inputs, and strengthening and supporting farmer cooperatives.

Keywords: Agroecological zones, spatial analysis, sustainable intensification, dynamic programming, production risk.

1 INTRODUCTION

Situated within the Great Rift Valley, Malawi has a broad diversity of agroclimatological conditions and landforms, resulting in considerable variations in crop suitability. Agroecological zones (AEZ) are geographical areas that exhibit similar climatic conditions influenced by latitude, elevation, temperature, and rainfall patterns (Sebastian 2009). Four AEZs can be broadly defined for Malawi: the Lower Shire Valley where elevations are less than 200 m above sea level, the Lakeshore Plains and Upper Shire River Valley found between 200 and 760 m in elevation; the Mid-altitude Plateau between 760 and 1300 m; and the Highlands which are those parts of Malawi with an elevation above 1,300 m. Each of the four AEZs has a unique combination of characteristics in terms of rainfall, temperature, altitude, landforms, soils, and agricultural practices. Such agroecological diversity implies that farming households in different AEZs adopt different cropping systems to maximize their productivity and profitably leverage in their farming the unique combinations of these features within their agroecological zone (World Bank 2019; Benson, Mabiso, and Nankhuni 2016; Sebastian 2009).

In addition, market considerations affect the cropping patterns that farming households use. The degree to which they can obtain commercial inputs and find good markets in which to sell their crops is taken into consideration by farming households as they plan what crops to produce and what cropping techniques to employ. In Malawi, access to markets is generally better in the more densely-populated regions of Southern and Central Malawi than in the North.

Considering the notable variations in agroecological conditions and market access across Malawi, we adjust the four AEZs noted earlier into six for our spatial analysis. This is done by combining the Mid-altitude Plateau and Highlands zones and splitting the Mid-altitude Plateau and Lakeshore zones by the regions of the country. For our analysis, we use the following six zones—Northern Mid-altitude Plateau (NMAP); Northern Lakeshore (NL); Central Mid-altitude Plateau (CMAP); Central and Southern Lakeshore (CSL); Southern Mid-altitude Plateau (SMAP); and Lower Shire Valley (LSV). These zones are mapped in Figure 1.1.

Significant diversity in agricultural production and marketing characteristics across the six AEZs implies that each zone will have unique comparative advantages in terms of smallholder cropping patterns. The AEZs differ in their environmental and agricultural conditions, which determine crop suitability; population density, which influences labor availability and average landholding sizes; and access to markets, which is influenced by the degree of urbanization in an AEZ. For example, although the NMAP and CMAP zones have similarities in terms of crop suitability, these AEZs are distinct from each other in terms of seasonality, market access, labor availability, and average landholding size due to differences in population densities and urbanization (NSO 2022; Matchaya et al 2014; Jayne et al. 2014). These factors have a significant impact on farming households' cropping choices, so, between the two AEZs, we see different cropping systems. Consequently, it is important to use spatial analysis in any assessment of the factors that influence the adoption of cereal-legume intercropping among smallholder farming households in Malawi.

Figure 1.1 Map of the six agroecological zones of Malawi

Source: Author.

In addition to agronomic crop suitability and adaptability factors, cultural preferences also make the cropping patterns in each zone unique. The crops produced in each zone follow not only each zone's unique weather or climatic conditions but also local cultural preferences and market demand patterns. For instance, although the two lakeshore AEZs are relatively climatically similar, cassava and maize both serve as the main staple crops in NL, while maize is the dominant staple in CSL. Similarly, pigeonpea is more commonly grown in CSL than in NL, reflecting a combination of both cultural preferences and agronomic suitability factors (Nsope and Nankhuni 2018; Makoka 2009; Snapp et al. 2003). Following a general approach in modeling that glosses over such spatial differences in agricultural production, therefore, may lead to inaccurate results and recommendations. Hence, it is important to consider spatial variations across regions when modeling farming households' crop choice and cropping system adoption behavior.

In this study, we extend the farm risk modeling work of Nindi (2021). This earlier study employed a single generalized approach to modeling the cropping system adoption behavior of an average smallholder farming household in Malawi. It was limited in that it took an average approach, which tends to be biased towards central tendencies and often overlooks important variations. In many contexts, the average approach fails to accurately represent all farming households across different agroecological zones. In this study, therefore, we seek to extend the modeling of smallholder farming households’ adoption behavior by taking into account spatial variation in key cropping and marketing characteristics of the farming systems. Particularly, we address two critical research questions, made apparent by the notable spatial variations in Malawi, including:

- Does location matter when modeling smallholder farming households’ adoption decisions?
- Does considering crop suitability and adaptability strengthen our understanding of cereal-legume intercropping adoption patterns across different regions?

We use AEZs to model spatial diversity, having broadly classified the country into six zones. Six AEZ-specific farm risk models are built and employed in the analysis.

This study was conducted under the Development-Smart Innovation through Research in Agriculture (DeSIRA) project. Under DeSIRA, researchers implement multidisciplinary studies to identify, develop, and test climate-resilient integrated technology options to address diverse challenges affecting the agricultural and food systems in Malawi. Investigating the impact of resource and market constraints and location-specific variations of those constraints on the adoption by farming households of sustainable intensification practices, as is done in the study here, directly supports the project's overarching goals of promoting sustainable agriculture intensification in Malawi. This study also aligns with the broader goal of the DeSIRA project, which is to enhance understanding of the opportunities for and constraints to uptake of integrated technology options that will improve farmers’ productivity and resilience to the adverse effects of climate change. By analyzing spatial variations in the constraints faced by farming households in different AEZs, this study contributes to the project's goal of developing smart and sustainable agricultural practices tailored to specific geographic and environmental conditions.

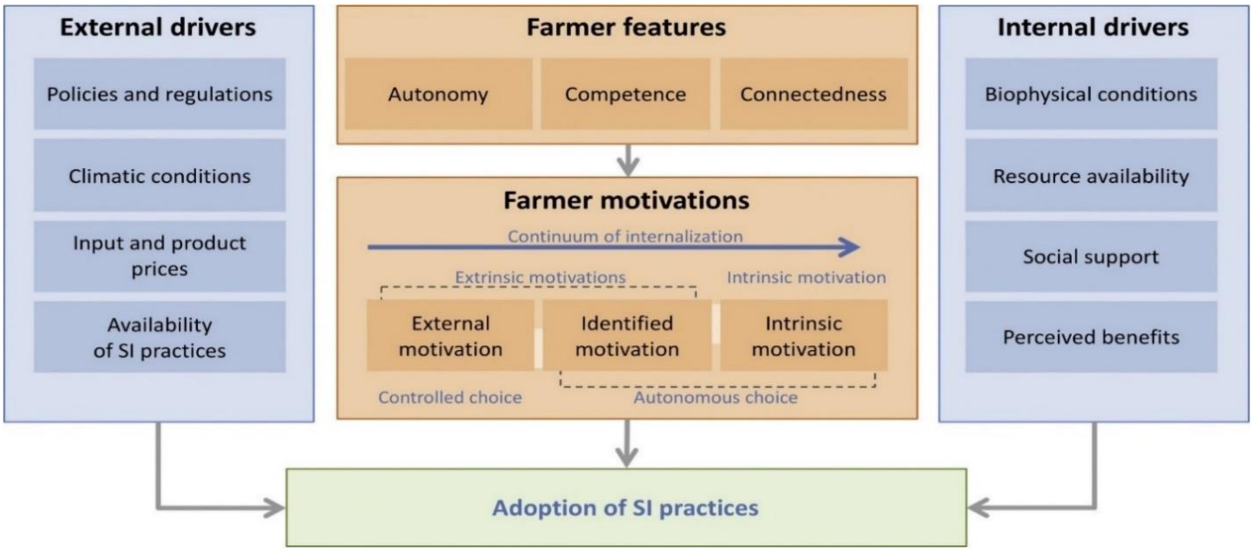
2 BACKGROUND

Intensifying the use of sustainable agricultural cropping methods is a widely recommended intervention strategy for reducing land degradation, conserving soils, and increasing land productivity (Pretty, Toulmin, and Williams 2011). Such methods encompass crop management methods and cropping systems that help to maintain and increase soil health and fertility and sustain natural resources and the environment. Cereal-legume intercropping is a popular, easy to implement, and sustainable intensification method that does not require heavy investments (Silberg et al. 2017). Although the benefits of such simple, sustainable intensification practices are widely documented and disseminated, most smallholder farming households in Malawi do not adopt and employ them (Ragasa 2019; Jambo et al. 2019; Kassie et al. 2015a).

2.1 Determinants of adoption of cereal-legume intercropping

Many factors influence smallholder farming households' adoption of sustainable intensification practices like cereal-legume intercropping (Figure 2.1). According to Silberg et al. (2017), commercial production of legumes and the use of other sustainable intensification practices like composting are associated with intercropping cereals and legumes in Malawi. Silberg, Richardson, and Lopez (2020) found that farming households favored intercropping as a weed management strategy. Mhango, Snapp, and Kanyama-Phiri (2013) also reported that limited access to improved seed and low yields were key constraints on farming households producing legumes. In addition, legumes, such as bean (*Phaseolus vulgaris*) and pigeonpea, are very susceptible to pests and diseases.

Figure 2.1 Factors affecting the adoption of sustainable intensification practices



Source: Jambo et al (2019)

Weak agricultural markets often result in farming households facing challenges in accessing higher value markets for their legume crops. Such marketing constraints have also been identified as a major obstacle preventing farming households from incorporating legumes into their cropping systems. More broadly, policy incentives, climatic conditions, and producer and consumer preferences are also key determinants of whether farming households decide to adopt sustainable agricultural intensification practices (Jambo et al. 2019).

Crop diversification through intercropping is more feasible for farming households with smaller holdings than planting a range of crops in pure stands. Silberg et al. (2017), found intercropping to be practiced on almost 60 percent of the plots in their study in Malawi. Nonetheless, intercropping of maize and legumes accounted for only 28 percent of the intercropped plots. Despite being the most advantageous type of intercropping in terms of raising crop yields, the adoption of maize-legume intercropping, is comparatively low (Kassie et al. 2015b; Silberg et al. 2017).

In this paper, our overall objective is to conduct a spatial analaysis of the adoption of maize-legume intercropping in Malawi by using an AEZ-specific approach to understand the factors that influence smallholder farming households' adoption decisions. We use the existing research literature to identify a number of the key constraints affecting farming households' adoption of cereal-legume intercropping (Tennhardt et al. 2024; Adamsone-Fiskovica and Grivins 2024; Manyanga, Pedzisa, and Hanyani-Mlambo 2023; Jones-Garcia and Krishna 2021; Kuyah et al, 2021; Jambo et al. 2019; Silberg et al. 2017 Mhango, Snapp, and Kanyama-Phiri 2013). Having identified pertinent factors affecting adoption, we then run General Algebraic Modeling System (GAMS) simulation models to understand which of these factors or constraints are most important in influencing farming households' cropping pattern choices. We consider both pure stand cropping of the three crops considered and three cereal-legume intercropping systems for each AEZ. Dynamic programming is used to evaluate the role of land and labor constraints and limited access to input and output markets on farming households' adoption of these cereal-legume intercropping systems in the six AEZs of Malawi.

2.2 Agroecological zone characteristics

As described earlier and as summarized in Table 2.1, six AEZs are used for the spatial analysis presented in this paper. In each zone, we simulate farming household's production decisions for four possible cropping systems over three years of planting and harvesting. We then compare the optimal production plans identified across these scenarios to the actual cropping patterns of farming households to gain insights into the role of resource and market constraints on farming households' adoption of sustainable agricultural intensification practices under risk.

2.2.1 Northern Mid-altitude Plateau

The Northern Mid-altitude Plateau (NMAP) zone covers all of Chitipa and Mzimba districts and the western part of Rumphi district. Most areas of this AEZ experience average rainfall of 800–1,200 mm annually. The elevation of most of NMAP is between 1,000 and 1,500 meters above sea level. However, the highland areas of the Misuku Hills and Nyika Plateau are above 1,500 meters in elevation. These highland areas receive over 1,200 mm of rainfall annually and have lower average temperatures than lower lying areas of NMAP. The farming population in the AEZ is estimated to be around 200,000 households with an average population density of 64 per square kilometer (NSO 2019).

The most commonly grown crops in NMAP are maize, bean, groundnut, soybean, and Irish potato. For the cereal-legume intercropping models for NMAP, we consider four cropping systems: each of the three crops considered planted in pure stand (T1), maize-bean intercropping (T2), maize-groundnut intercropping (T3), and double-up bean-groundnut intercropping (T4), in which the two legume crops are planted at about the same time, but, as their growth cycles differ, they are harvested at different times (Smith et al. 2016).

Table 2.1 Cropping system evaluated, by agroecological zone

Agroecological zone	Districts	Crops considered	Cropping systems evaluated (technology options)
Northern Mid-altitude Plateau	Chitipa, Rumphi (west), Mzimba	Maize, bean, groundnut	T1: Each of the three crops planted in pure stands T2: Maize–bean intercrop T3: Maize–groundnut intercrop T4: Double-up groundnut-bean intercrop
Northern Lakeshore	Karonga, Rumphi (east), Nkhata Bay, Likoma	Maize, cassava, pigeonpea	T1: Each of the three crops planted in pure stands T2: Maize–cassava intercrop T3: Maize–pigeonpea intercrop T4: Cassava–pigeonpea intercrop
Central Mid-altitude Plateau	Kasungu, Ntchisi, Dowa, Lilongwe, Mchinji, Dedza, Ntcheu	Maize, bean, groundnut	T1: Each of the three crops planted in pure stands T2: Maize–bean intercrop T3: Maize–groundnut intercrop T4: Double-up groundnut-bean intercrop
Central and Southern Lakeshore	Nkhotakota, Salima, Mangochi, Balaka, Machinga	Maize, pigeonpea, groundnut	T1: Each of the three crops planted in pure stands T2: Maize–pigeonpea intercrop T3: Maize–groundnut intercrop T4: Double-up groundnut-pigeonpea intercrop
Southern Mid-altitude Plateau	Zomba, Chiradzulu, Mulanje, Thyolo, Neno, Blantyre, Mwanza, Phalombe	Maize, pigeonpea, groundnut	T1: Each of the three crops planted in pure stands T2: Maize–pigeonpea intercrop T3: Maize–groundnut intercrop T4: Double-up groundnut-pigeonpea intercrop
Lower Shire Valley	Chikwawa, Nsanje	Sorghum, pigeonpea, groundnut	T1: Each of the three crops planted in pure stands T2: Sorghum–pigeonpea intercrop T3: Sorghum–groundnut intercrop T4: Double-up groundnut-pigeonpea intercrop

Source: Author's compilation.

2.2.2 Northern Lakeshore

The Northern Lakeshore (NL) zone covers all of Karonga, Nkhata Bay, and Likoma districts and the eastern part of Rumphi district. The zone lies between 400 to 1,000 meters above sea level. Rainfall ranges from 600 to 800 mm annually, although areas of Nkhata Bay receive much more rainfall. The areas are characterized by very fertile alluvial soils and high average temperatures. The farming population in the AEZ is estimated to be around 200,000 households, with an average population density of 87 per square kilometer (NSO 2019). The most commonly grown crops in NL are maize, rice, cassava, bean, and groundnut. For this zone, the four cropping systems modeled are each of the three crops considered planted in pure stand (T1), maize-cassava intercropping (T2), maize-pigeonpea intercropping (T3), and cassava-pigeonpea intercropping (T4).

2.2.3 Central Mid-altitude Plateau

The Central Mid-altitude Plateau (CMAP) zone covers Dowa, Kasungu, Lilongwe, Ntchisi, Mchinji, Dedza, and Ntcheu districts. The zone annually receives rainfall ranging from 800 to 1,200 mm. The zone is situated at an elevation between 1,000 to 1,500 meters. The Kasungu–Lilongwe Plain, typically known as Malawi's breadbasket, is part of this agroecological zone. The farming population is estimated to be around 1.7 million households with a population density of 211 people per square kilometer (NSO 2019). There are highland areas in the AEZ in Dowa, Ntchisi, Dedza, and Ntcheu districts that are at an elevation of over 1,500 meters. The highland areas receive over 1,200 mm of rainfall annually and have lower average temperatures than the mid-altitude areas of the zone. The most common crops for CMAP are maize, bean, groundnut, soybean, sweet potato, and Irish potato. For the cereal-legume intercroping modeling for the zone, we consider each of the three crops considered planted in pure stand (T1), maize-bean intercropping (T2), maize-groundnut intercropping (T3), and maize with double-up bean-groundnut intercropping (T4).

2.2.4 Central and Southern Lakeshore

The Central and Southern Lakeshore (CSL) zone covers Mangochi, Machinga, Balaka, Nkhotakota, and Salima districts. The elevation of the zone is between 400 to 1,000 meters above sea level. Rainfall is lower than in neighboring mid-altitude areas, ranging from 600 to 800 mm annually. CSL also experiences relatively high average temperatures. The farming population in the zone is about 1.5 million households with a population density of 178 people per square kilometer (NSO 2019). The four cereal-legume intercropping systems considered in our analysis for CSL are each of the three crops considered planted in pure stand (T1), maize-pigeonpea intercropping (T2), maize-groundnut intercropping (T3), and maize with double-up groundnut-pigeonpea intercropping (T4).

2.2.5 Southern Mid-altitude Plateau

The Southern Mid-altitude Plateau (SMAP) zone covers Blantyre, Thyolo, Phalombe, Chiradzulu, Mulanje, Neno, Mwanza, and Zomba. The zone receives relatively high average annual rainfall of between 800 and 1,200 mm. The elevation of the zone is between 1,000 and 1,500 meters above sea level. There are some highland areas in SMAP at an elevation over 1,500 meters above sea level. These highlands receive over 1,200 mm of rainfall annually and experience lower average temperatures than do lower elevation areas of SMAP. The farming population of the zone is approximately 1.8 million households. With a population density of 250 people per square kilometer, SMAP is the most densely populated of the six AEZs of Malawi (NSO 2019). The commonly grown crops for this AEZ include maize, groundnut, pigeonpea, bean, sweet potato, and Irish potato. The four cereal-legume intercropping systems considered in our analysis for SMAP are each of the three crops considered planted in pure stand (T1), maize-groundnut intercropping (T2), maize-pigeonpea intercropping (T3), and maize with double-up bean-groundnut intercropping (T4).

2.2.6 Lower Shire Valley

The Lower Shire Valley (LSV) zone lies between 30 to 500 meters above sea level in elevation and is comprised of the two southernmost districts of Malawi—Chikwawa and Nsanje. This AEZ is the driest of the six AEZs of Malawi, receiving, on average, less than 600 mm of rain annually. As a consequence, rain-fed farming of most crops in LSV is challenging. Although maize is commonly grown in the AEZ, more adapted crops for the zone are sorghum, pigeonpea, and millet. A much wider range of crops can be grown in areas suitable for irrigated farming, especially vegetables and maize. LSV has an estimated population of 200,000 households and a population density of about 250 people per square kilometer (NSO 2019; Matchaya et al. 2014). The four cereal-legume intercropping systems considered in our analysis for LSV are each of the three crops considered planted in pure stand (T1), sorghum-pigeonpea intercropping (T2), sorgum-groundnut intercropping (T3), and groundnut-pigeonpea intercropping (T4).

3 METHODOLOGY

This section provides detailed information about the dynamic model on how it was setup to reflect the specific conditions of the six AEZs, the variables and constraints used in each AEZ-specific models, and the scenarios run in each model.

3.1 Set up of the agroecological zone-specific models

Our overall objective in this research is to explore the spatial factors that influence smallholder farming households' adoption of maize-legume intercropping systems in Malawi. To identify factors and constraints that may affect adoption of cereal-legume intercropping, we use findings from the research literature on smallholder cropping systems in Malawi and the region (Tennhardt et al. 2024; Adamsone-Fiskovica and Grivins 2024; Manyanga, Pedzisa and Hanyani-Mlambo 2023; Jones-Garcia and Krishna 2021; Kuyah et al. 2021; Jambo et al. 2019; Silberg et al. 2017; Mhango, Snapp, and Kanyama-Phiri 2013). These then are built into General Algebraic Modeling System (GAMS) simulation models to enable us to understand better which of these factors and constraints are most important in influencing farming households' decisions on the cropping systems they use.

We employ discrete stochastic programming (Rae 1971) to create models of technology adoption by smallholder farming households in the six agroecological zones in Malawi. Each of the AEZ-specific models follows a similar model setup and uses the same set of underlying premises. We consider common cereal-legume cropping systems for each zone in which farming households grow three types of crops: a staple food crop, such as maize; a cash crop, usually a legume; and another crop, which is either a legume or a staple.

The farming households' cropping year is divided into two periods based on the main rainfed cropping season (FAO 2021). The lean or planting season runs between October and March, while the harvest season runs from April to August.[1] For the NMAP and NL zones, the models are constructed so that planting and harvesting decisions take place in January and June, respectively. For the CMAP and CSL zones, these decision points are assumed to be in December and May, respectively. For the two AEZs wholly in the southern region, the SMAP and LSV zones, we consider planting and harvesting decisions to take place in November and April, respectively.

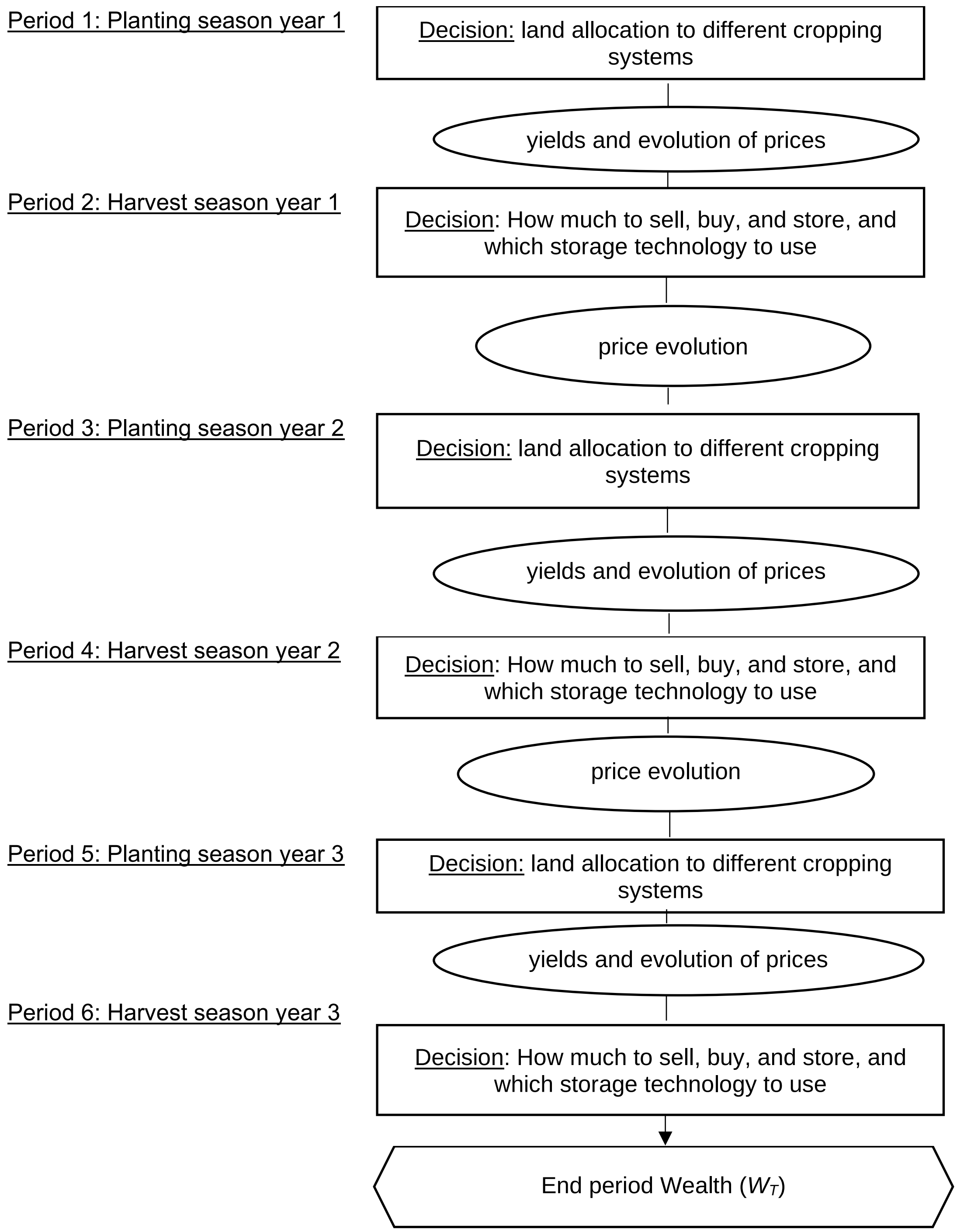
Figure 3.1 shows, as a generic stochastic process, the flow of the decision stages over three crop production cycles for the six AEZ-specific discrete stochastic programming models. To capture the medium to long-term effects of sustainable intensification practices like intercropping, we employ finite-horizon models that have a total of six decision stages spanning three cropping years. We assume that in each zone the average farming household makes decisions sequentially from planting year 1 to harvest year 3 with the goal of maximizing end-of-period expected wealth.

The rectangles in Figure 3.1 show the decision stages and corresponding decisions that the farming household makes in each. The circles in the figure show the random variables and their evolution across stages. The polygon at the end shows the ending period wealth—farming households make sequential decisions with the goal of maximizing the expected end-of-period wealth. Some key non-random parameters in the model include initial endowments of resources, including cash, maize, and groundnut stocks in planting period 1,

[1]A relatively small share of farming households produce crops during the irrigated dimba season in the dry period of the year. According to IHS survey data, 8.8 percent of farming households engaged in dimba cropping in 2016 and 18.8 percent in 2019. As dimba farming is not representative of ordinary smallholder farming households, for simplicity, we have excluded dimba cropping from our model.

and cash remittances and income in each period, which are used for meeting typical expenses, including school fees, groceries, and utilities.

Figure 3.1 Generic discrete stochastic programming model timeline



Source: Author's compilation.

For the stochastic part of the models, we assume that yields and prices are the primary random variables that the farm household deals with during the decision-making process. These random variables evolve between the decision stages as the seasons move from planting to harvest. However, only prices evolve from the harvest to planting periods. Prices are considered to be jointly distributed with yields and are assumed to follow an autoregressive process. This is empirically approximated using the Gaussian quadrature method. Yields are assumed to be influenced by random weather effects. These also are empirically approximated using the Gaussian quadrature method.

For each zone, four cropping systems that involve a cereal and two legumes (or a legume and cassava in NL) are considered in the model. The first cropping system is made up of pure stands of each of the three crops considered. The second is an intercrop of the cereal with the first legume, while the third is an intercrop of the cereal with the second legume (in NL, with cassava). The fourth cropping system is, except in NL, cereal with a double-up intercrop of the two legumes. (In NL, the fourth cropping system is an intercrop of cassava and the legume.)

At the planting stage, the farming household chooses what mix of the four cropping systems to employ on his or her cropland. That is, the farming household decides how much of the cropland to allocate to each of the different cropping systems. We assume that for the three systems involving intercropping, T2, T3, and T4, the share of land allocated to each crop within the system is equal and follows a one-to-one ratio.

In this manner, farming households are making a set of sequential conditional decisions under risk with the objective of maximizing ending wealth or profit, i.e., wealth at the end of the three cropping years.

3.2 Variables and constraints in the agroecological zone-specific models

Here we discuss the variables and the relationships between these variables and the parameters that define the constraints in the model.[2] For each zone, we assume the farming household has three primary production resources—land, labor, and cash. We have accounting constraints at each stage that use the realized state of nature to track the farming household's use of each of the three resources and to make sure the amount of resources used in any period is equal to or less than the sources or endowments of these resources. The farm household's expected ending wealth or profit maximization objective is then optimized subject to these resource accounting constraints.

In the planting period of each year, the total amount of land allocated to the three crops in the various cropping systems used by the farming household cannot exceed the endowment of the household's farmland. This is a single constraint for year one. For years two and three, a set of land constraints applies—one for each realization of the sequence of random variables that occurs in a given period. As such, beyond the year one planting period, the number of constraints is conditional on the sequence of random variables that have been realized up to the given decision stage. We also have constraints that restrict labor use to be no greater than the endowment of family labor plus hired labor for each planting and harvest period.

In each decision stage, we track the quantities of inventory held by the farming household—namely maize, bean, pigeonpea, and cash using some accounting constraints to make sure that the "uses" of the resources do not exceed the "sources" in each decision period, conditional on the random variables that have been realized up to that decision period. For the crops, these constraints are expressed in kilograms, while the cash constraint is expressed in the local Malawi Kwacha currency (In 2024, USD 1.00=MK 1,700). The other constraint relates to grain storage in each period. It limits the smallholder farming household's storage to the total quantity of crop inventory that the farming household can hold in its storage facilities. This constraint reflects the farming household's secure storage

[2] The full model is described in Brooke et al. (1997).

space. For the grain storage constraints, we also factor in post-harvest losses, as the research literature shows that these are taken into account in farmers' decision-making processes (Al Shoffe and Johnson 2024; Mutungi et al. 2023). Here we use estimates of post-harvest losses from the African Postharvest Losses Information System (APHLIS) and some estimates from past research studies.

3.3 Model scenarios

In order to understand how the resource and market constraints that farming households face in each AEZ influence their cropping system choices under risk, we simulate the farming household's production decisions for six different scenarios or states of the world (Table 3.1). We then compare the optimal production plans across these scenarios. Across the AEZs, the scenario assumptions are similar, however, the status quo scenario for each AEZ is distinct as it is premised on the average conditions within the zone. In our analysis of the results of the modeling, we compare adoption patterns across AEZs to assess how spatial variation in resource and market constraints may influence patterns of adoption of different types of intercropping systems as sustainable agricultural intensification practices.

Table 3.1 Summary of the underlying premises for each model scenario

scenario	Details	Parameter or model changes
1: Status quo	AEZ-specific baseline scenario	None
2: Labor	Relaxed labor constraints	Labor endowments of farming households are doubled to simulate the impact of relaxing labor constraints on smallholder farming households.
3: Land	Relaxed land constraints	Landholding is increased by 20 percent to simulate the impact of relaxing land constraints on smallholder farming households.
4: Input market	Increased access to input markets (improved legume seed).	Doubling legume yields due to increased access to and use of high yielding legume varieties.
5: Output market	Increased access to output markets (higher legume prices).	Doubling of legume prices due to increased access to high value legume markets.
6: Unconstrained	Relaxed labor, land, and market constraints	Labor endowments are doubled, land endowments are increased by 20 percent, and legume yields and prices are doubled.

Source: Author's compilation.

Scenario 1 is the status quo. It represents a state of the world where households face both resource—land and labor—and input and output market constraints. For this scenario, we use data from the Integrated Household Survey (IHS) for Malawi to inform landholding levels and labor availability for the average representative farm household in each AEZ. Similarly, the expected and realized prices and yields for this scenario are based on actual historical data for each zone. This data is used to approximate the empirical distributions of prices and yields used in the AEZ-specific models.

Scenario 2 is the state of the world where households face the status quo for the zone but with relaxed labor constraints. However, market and land constraints remain at existing levels—farming households simply have more labor available than in the status quo scenario. Specifically, the total labor hours available for a farm household in each period are doubled in this scenario. The idea of modeling this state of the world is to show the impact of labor constraints on households' choice of cropping systems.

Scenario 3 is the state of the world where farming households face labor and market constraints similar to the status quo but with a relaxation of the land constraints. Specifically, the farming household's landholding is increased by 20 percent in this scenario. This is done to assess the impact of land constraints on the choice of cropping systems by farming households.

Scenario 4 is also the state of the world similar to the status quo, except that households have access to seed of high-yielding legume varieties due to improvements in agricultural input markets. In this scenario, we double the realized yields for legumes in the status quo (baseline) scenario and evaluate the impact of these higher yields, which are assumed to result from growing improved legume varieties, on the farming households' choice of cropping systems.

Scenario 5 is the state of the world similar to the status quo except that households are considered to have access to high-value output markets which offer them higher prices for the legumes they produce. In this scenario, farming households obtain legume output prices that are doubled from the prices they realize in the status quo (baseline) scenario.

Scenario 6 is an unconstrained scenario in which farming households do not face any agricultural resource or input and output market constraints. In this scenario, we run the models considering a state of the world where the farm household has double the labor and 20 percent more land that they have in the status quo (baseline) scenario and have access to seed for high-yielding legume varieties through effective agricultural input markets and to higher prices for the legumes they produce through improved access to high-value legume output markets. This scenario helps illustrate the impact of alternative policies that together jointly address these constraints on farming households' production decisions.

After running the six scenarios in the AEZ-specific models, we then compare the farm household's optimal decisions seen across the scenarios to illustrate the impacts of these constraints on farming households' choice of intercropping systems as sustainable agricultural intensification practices.

4 DATA AND DATA SOURCES

To generate key parameters for modeling the adoption decisions of smallholder farming household, we use data from several sources (Table 4.1). These include:

- Data from the Fifth Integrated Household Survey (IHS) for Malawi conducted in 2019/20 by the National Statistical Office;
- Data from FAOSTAT, the public international database of the Food and Agriculture Organization of the United Nations;
- Data from the Agricultural Production Estimates of the Ministry of Agriculture;
- Data from the Agricultural Markets Information System of the Ministry of Agriculture.
- Economic data collected by the International Institute of Tropical Agriculture (IITA) from DeSIRA trials across Malawi; and
- Pluralistic agricultural extension survey data collected by the International Food Policy Research Institute (IFPRI) in 2018.

Table 4.1 Summary of data and sources

Parameters for Baseline scenario	Details	Units	Sources
Prices	2001 to 2023 (monthly)	(MK/kg)	FAO / Agricultural Market Information System
Yields	2001 to 2023 (annual)	(kg/acre)	FAO / Agricultural Market Information System DeSIRA field trial data for model validation
Yields variations by cropping system	Literature	(kg/acre)	Holden 2020; Mutenge et al. 2019; Nyagumbo et al. 2020.
Grain consumption	2019/20 household survey	Kg	IHS5 Household module G1to G3
Fertilizer use	2019/20 household survey	MK	IHS5 Agricultural Module D
Fertilizer use by cropping system	Literature	(kg/ac)	Holden 2020; Mutenge et al. 2019; Nyagumbo et al. 2020.
Labor	2019/20 household survey	hours	IHS5 Agricultural Module D; Household Module E
Labor use by cropping system	Literature	(kg/acre)	Holden 2020; Mutenge et al. 2019; Nyagumbo et al. 2020.
Land	2019/20 household survey	acre	IHS5 Household Module F
Post-harvest loss (PHL)	Recent estimates	loss rate, %	APHLIS 2022, other research literature
Transaction costs	Recent estimates	MK	IHS5 Household Module I (Transportation)
Initial endowments	Recent estimates	kg, MK	IHS5 Agriculture Module I (Storage)
Variable costs	Recent estimates	MK	IHS5 Agricultural Module D, E, F; DeSIRA/IITA economic data.
Inventory capacity	Recent estimates	kg	IHS5 Household Module M; Agriculture Module I, O (Storage)
Minimum wage	2023 Ministry of Labor	MK/hour	Ministry of Labor

Source: Author's compilation.

For crop yields, we use annual yield data for Malawi as reported in FAOSTAT from 2001 to 2023. Supplementary yield data for different intercropping systems are based on yield estimates from the research literature and data from field trials carried out across Malawi under the DeSIRA project. These supplementary datasets on yields were also used for model validation.

Similarly, the specific input and labor requirements per unit of land by cropping system are also based on estimates from the research literature (Holden 2020).

For price data, we use historical data collected through the Agricultural Markets Information System of the Ministry of Agriculture. This data system was built to inform the Ministry's food security policies in collaboration with FAO's Global Information and Early Warning System. These price data are collected daily for key food crops in major commodity markets, which are used to derive the weekly and monthly average prices reported by the Ministry. We used the reported national average monthly price data from 2001 to 2023, adjusted to account for inflation using the Consumer Price Index for Malawi obtained from the World Bank with January 2023 as the base year.

Other key parameters for the model include, among others, household demographics, such as average household size; endowments of labor and land; production inputs and costs of those inputs; minimum grain consumption requirements; average monthly household expenditure; average labor use for planting and harvest per acre; average monthly income; and average grain storage capacity. These parameters are based on estimates from the research literature, Key Facts Sheets for Malawi developed by IFPRI from the third IHS of 2010/11 and the fourth IHS of 2016/17 (IFPRI-Malawi 2018), and own calculations using data from the fifth IHS of 2019/20 (Table 4.1).

One of the key challenges experienced was the limited availability of high-quality historical data from crop field trials. As such, we were only able use historical agronomic field trial data on crop yields for parametrization and validation. Most of the data was limited in three ways:

- Much of the field trial and economic data available only provided single observations for the AEZs instead of time series. Time series data was required for the model simulations.
- Although the analysis required data from all six AEZs, most of the trials from which data could be obtained were not national in scope, but limited to a few AEZs. Data was not available particularly for the NMAP and NL zones
- The trial data did not cover all crops. For example, there were no trials that provided yield data on cassava or sorghum.

The parameters for each of the six AEZ-specific models that were obtained from these and other data sources are presented in Table 4.2.

Table 4.2 Model parameters—baseline scenarios of the agroecological zone-specific models

Parameter	Unit	NMAP	NL	CMAP	CSL	SMAP	LSV	Source
Landholding	acres	2.3	2.2	2.0	1.8	1.5	1.2	IHS5 Agriculture Module C
Household expenditure	MK/mo.	42,932	53,906	28,575	32,833	46,797	29,688	IHS5 Household Mod. I
Maize consumption	kg/mo.	23.0	18.6	39.6	32.6	37.3	35.4	IHS5: HH Mod. G1 to G3
Pigeonpea consumption	kg/mo.	0.1	0.3	0.01	0.8	1.8	1.7	IHS5: HH Mod. G1 to G3
Bean consumption	kg/mo.	2.5	1.8	55.1	1.4	1.5	2.0	IHS5: HH Mod. G1 to G3
Ground nuts consumption	kg/mo.	3.9	2.0	2.4	3.0	1.8	0.9	IHS5: HH Mod. G1 to G3
Cassava consumption	kg/mo.	3.8	20.3	2.4	3.0	4.3	1.9	IHS5: HH Mod. G1 to G3
Sorghum consumption	kg/mo.	0.005	0.001	0.005	0.3	0.5	6.1	IHS5: HH Mod. G1 to G3

Parameter	Unit	NMAP	NL	CMAP	CSL	SMAP	LSV	Source
Household size	persons	4.0	4.5	4.5	5.0	5.0	5.0	IHS5 aggregate consumption per capita
PHL (post-harvest loss) maize	%/mo.	19.2	19.2	19.2	19.2	19.2	19.2	APHLIS 2022
PHL pigeonpea	%/mo.	7.3	7.3	7.3	7.3	7.3	7.3	Abdoulaye et al. 2016
PHL bean	%/mo.	12.0	12.0	12.0	12.0	12.0	12.0	Ambler et al. 2018
PHL groundnut	%/mo.	13.7	13.7	13.7	13.7	13.7	13.7	Tsusaka et al. 2017
PHL cassava	%/mo.	7.0	7.0	7.0	7.0	7.0	7.0	Kikulwe 2017
PHL sorghum	%/mo.	10.7	10.7	10.7	10.7	10.7	10.7	APHLIS 2022
Inventory capacity	kg	1,500	1,500	1,500	1,500	1,500	1,500	IHS5 HH Mod. M; Agric. Mod. I and O: Storage
Trade capacity	kg/mo.	250	250	250	250	250	250	IHS5 HH Mod. M; Agric. Mod. I and O: Sales
Wage per hour	MK/hr.	404	539	357	598	480	672	IHS5: HH Mod. E: waged jobs
Hired labor hours	hr./wk./ person	31.0	32.0	30.2	31.0	31.4	28.2	IHS5: HH Mod. E: waged jobs
Available hired labor harvest period	hr./ harvest season	17.5	3.0	43.5	5.3	22.0	1.3	IHS5 Data: Agric. Mod. D; HH Mod. E
Family agricultural labor	hr./wk./ person	10.5	11.0	12.5	11.5	15.0	12.0	Malawi IHS4 Report (pages 6-8)
Available family labor	hr./ season	704	880	1,000	920	1,200	880	Imputed IHS5 report (pages 6-8); HH size
Enterprise revenue	MK/ mo.	13,709	14,652	99,282	93,720	90,414	84,017	IHS5: HH Mod. N2
Other cash sources	MK/ mo.	6,151	6,458	6,881	1,854	4,829	1,574	IHS5: Agric. Mod. P: Other income
Cash (wages + other transfers)	MK/ mo.	31,000	31,000	44,296	54,296	35,000	35,000	IHS5: Agric. Mod. P: Other income
Cash savings (initial endowment)	MK (2016)	59,957	70,403	85,500	57,660	64,951	45,519	IHS5: HH Mod. P: Incomes
Maize stocks (init. endow.)	kg	82.4	4.8	92.1	23.0	32.8	5.2	IHS5: Agric. Mod. I Sales and Storage
Pigeonpea stocks (init. endow.)	kg	0.0	4.4	0.0	26.1	40.7	106.0	IHS5: Agric. Mod. I: Sales and Storage
Bean stocks (init. endow.)	kg	15.6	2.0	21.6	225.3	17.4	25.0	IHS5: Agric. Mod. I Sales and Storage
Groundnut stocks (init. endow.)	kg	5.0	0.1	5.7	3.0	1.0	0.2	IHS5: Agric. Mod. I Sales and Storage
Cassava stocks (init. endow.)	kg	11.6	122.5	0.0	179.1	89.4	198.0	IHS5: Agric. Mod. Q
Sorghum stocks (init. endow.)	kg	2.0	0.0	0.0	37.3	26.6	110.7	IHS5: Agric. Mod. I Sales and Storage

Source: Author.
Note: CMAP = "Central Mid-altitude Plateau zone"; CSL = "Central and Southern Lakeshore zone"; LSV = "Lower Shire Valley zone"; NL = "Northern Lakeshore zone"; NMAP = "Northern Mid-altitude Plateau zone"; SMAP = "Southern Mid-altitude Plateau zone"

5 RESULTS FOR THE AGROECOLOGICAL ZONE-SPECIFIC MODELS

To understand the role of location-specific resource and market constraints on the choices farming households make relative to crop production under risk, we use the AEZ-specific models to simulate production decisions under the six scenarios and compare the optimal production plans across these scenarios. In this section, we present key results for each of the six AEZ-specific farm risk models.

5.1 Northern Mid-altitude Plateau zone

For the NMAP model, we considered maize, bean, and groundnut. The cropping systems we analyzed were maize (T1M), groundnut (T1G), and bean (T1B) in pure stands; a maize-bean intercrop (T2); a maize-groundnut intercrop (T3), and a double-up bean-groundnut intercrop (T4). Key findings from the NMAP model scenario results are presented in Table 5.1.

Table 5.1 Optimal cropping plan—Northern Mid-altitude Plateau zone

	Year 1		Year 2		Year 3	
Optimal mix	Land allocation, avg., acres	Share, %	Land allocation, avg., acres	Share, %	Land allocation, avg., acres	Share, %
Baseline scenario (1)						*Landholding, avg.: 2.30 acres*
T1M	1.679	73	1.863	81	1.840	80
T2	0.621	27	0.437	19	0.460	20
Labor policy (doubling of available labor) scenario (2)						*Landholding, avg.: 2.30 acres*
T1M	0.989	43	1.127	49	1.012	44
T2	1.311	57	1.173	51	1.288	56
Land policy (20 percent more cropland) scenario (3)						*Landholding, avg.: 2.76 acres*
T1M	1.518	55	0.964	36	0.856	31
T2	1.242	45	1.794	64	1.904	69
Input market policy (legume yields doubled) scenario (4)						*Landholding, avg.: 2.30 acres*
T2	1.610	70	1.725	75	1.817	79
T3	0.690	30	0.575	25	0.483	21
Output market policy (legume prices doubled) scenario (5)						*Landholding, avg.: 2.30 acres*
T2	1.495	65	1.334	58	1.403	61
T4	0.805	35	0.966	42	0.897	39
Unconstrained (all four modifications jointly) scenario (6)						*Landholding, avg.: 2.76 acres*
T2	0.690	25	1.325	48	0.828	30
T4	2.070	75	1.435	52	1.932	70

Source: Author.
Note: Cropping systems assessed were maize (T1M), groundnut (T1G), and bean (T1B) in pure stands; maize-bean intercrop (T2); maize-groundnut intercrop (T3), and double-up bean-groundnut intercrop (T4).

In scenario 1, which is the status quo or baseline scenario in which households face the actual resource (land and labor) and market (input and output) constraints pertinent to their AEZ, the farming household mostly takes on a subsistence approach where the optimal production plan has maize grown in pure stand (T1M) dominating the share of land throughout the 3-year planning horizon—73 to 81 percent of farmland is allocated to T1M over the three years. However, the maize-bean intercrop (T2) is observed to be an optimal allocation for some of the cropland. The maize-groundnut intercrop (T3) and the double-up bean-groundnut intercrop (T4) are not in the optimal solution plan for the entire three-year planning horizon.

In scenario 2, in which the labor constraints are relaxed by doubling the available labor, our model shows that the production technology mix is not different from the baseline scenario—the optimal production plan still only has T1M and T2. However, relative to scenario 1, we observe that the farm household increases the land allocated to the maize-bean intercropping option (T2) consistently over the three years—on average, intercropping increases by about 27 percent over the three years relative to the baseline scenario. This is probably driven by the household's need to maximize returns from their limited land by ensuring output from multiple crops through intercropping, which is relatively more labor-intensive than producing maize in a pure stand.

In scenario 3, in which land constraints are relaxed through a 20 percent increase in household landholdings, the optimal technology mix does not change from the baseline scenario with only T1M and T2 in the optimal production plan. However, as with the scenario in which labor constraints were relaxed, the land scenario results in the agricultural households increasing the land they allocate to maize-bean intercropping (T2) from, on average, 22 percent of their land over the three years in the baseline scenario to about 60 percent in the land scenario (3).

In scenario 4, in which farming households realize a doubling in legume yields due to better access to improved seed, relative to the baseline scenario, the optimal production plan for farming households shifts to maize-legume intercropping from pure stand maize production. In this scenario, the optimal production plan involves a mixture of the maize-bean intercrop (T2) and maize-groundnut intercrop (T3). Improved access to seed for high-yielding legumes, which directly translates into higher legume yields, results in farming households integrating more legumes into their cropping systems.

Scenario 5 assesses the optimal production plan for farming households when they have access to higher-value markets in which to sell the legume crops—both expected and realized prices are doubled from the baseline model.[3] In this output market scenario, the optimal strategy for farming households is to integrate more legumes into their cropping through including maize-bean intercropping (T2) and double-up bean-groundnut intercropping (T4). In this scenario, the optimal mix for farming households is to allocate about 60 percent of their land to maize-bean intercropping and the rest to double-up bean-groundnut intercropping.

Scenario 6 models the impact for farming households of implementing jointly all the alternatives considered in scenarios 2 to 5. In scenario 6, the results are similar to scenario 5—only maize-bean intercropping (T2) and double-up bean-groundnut intercropping (T4) feature in the optimal production plan. However, relative to scenario 5, the farming household should increase the cropland allocated to double-up bean-groundnut intercrop to about 65 percent, on average, across the three-year planning period. This suggests that increasing access to legume input and output markets and increasing access to land and labor will push the farming household towards a more strongly legume-based cropping pattern.

5.2 Northern Lakeshore zone

For the NL model, we considered maize, cassava, and pigeonpea. The cropping systems we analyzed were maize (T1M), cassava (T1C), and pigeonpea (T1P) in pure stands; a maize-cassava intercrop (T2); a maize-pigeonpea intercrop (T3), and a cassava-pigeonpea intercrop (T4). Key findings from the NL model scenario results are presented in Table 5.2.

[3] As with scenario 3, market policies in scenario 4 are implemented indirectly in modeling the impact of these marketing policies on farming households' decision under risk.

Table 5.2 Optimal cropping plan—Northern Lakeshore zone

Optimal mix	Year 1 Land allocation, avg., acres	Year 1 Share, %	Year 2 Land allocation, avg., acres	Year 2 Share, %	Year 3 Land allocation, avg., acres	Year 3 Share, %
Baseline scenario (1)						*Landholding, avg.: 2.20 acres*
T1C	0.902	41	0.440	20	0.880	40
T2	1.298	59	1.760	80	1.320	60
Labor policy (doubling of available labor) scenario (2)						*Landholding, avg.: 2.20 acres*
T1C	0.682	31	0.286	13	0.836	38
T2	1.518	69	1.914	87	1.364	62
Land policy (20 percent more cropland) scenario (3)						*Landholding, avg.: 2.64 acres*
T2	0.686	23	0.449	17	0.317	12
T4	1.954	77	2.191	83	2.323	88
Input market policy (legume yields doubled) scenario (4)						*Landholding, avg.: 2.20 acres*
T3	0.660	30	0.616	28	0.462	21
T4	1.540	70	1.584	72	1.738	79
Output market policy (legume prices doubled) scenario (5)						*Landholding, avg.: 2.20 acres*
T3	0.330	15	0.484	22	0.154	7
T4	1.870	85	1.716	78	2.046	93
Unconstrained (all four modifications jointly) scenario (6)						*Landholding, avg.: 2.64 acres*
T3	0.264	10	0.317	12	0.132	5
T4	2.376	90	2.323	88	2.508	95

Source: Author.
Note: Cropping systems assessed were maize (T1M), cassava (T1C), and pigeonpea (T1P) in pure stands; maize-cassava intercrop (T2); maize-pigeonpea intercrop (T3), and cassava-pigeonpea intercrop (T4).

In scenario 1, the baseline simulation, farming households in NL mostly take a subsistence approach with staples dominating the optimal production plan. The optimal strategy for the scenario has cassava in pure stand (T1C) and the maize-cassava intercrop (T2) only throughout the three-year planning horizon.

Scenario 2, in which labor constraints are relaxed by doubling the available labor, shows that the farming household's technology mix is not different from the baseline scenario—the optimal plan still has the staple crops cassava and maize dominating with no changes or shift to legume-integrated cropping system. This may imply that labor is not a binding constraint to cropping choices within the zone, so increasing available labor does not result in a change in cropping systems relative to the baseline.

In scenario 3, in which land constraints are relaxed through a 20 percent increase in household landholdings, a change in the optimal technology mix is seen with legumes integrated into the optimal cropping system. The increase in land influences the farm household in the zone to include the cassava-pigeonpea intercrop (T4) in the optimal plan, switching from cassava in pure stand (T1C).

In scenario 4, in which legume yields are doubled, an increased integration of legumes in the optimal cropping mix of farming households is observed relative to the baseline scenario. Legumes are now grown over the entire landholding—the maize-pigeonpea intercrop (T3) and the cassava -pigeonpea intercrop (T4). The higher expected pigeonpea yields likely influenced the farm household to integrate more pigeonpea into the cropping system. The optimal plan has more land allocated to T4 than T3, likely because cassava and pigeonpea are relatively better adapted than maize to the dry spells which often affect the NL zone.

Scenario 5 simulates households having access to higher prices for their legume output—legume prices are doubled from the baseline scenario. Similar to scenario 4, in scenario 5 NL farming households incorporate more legumes in their optimal cropping mix—maize-pigeonpea intercrop (T3) and cassava-pigeonpea intercrop (T4). However, relative to the increased yield scenario (4), in this scenario (5) of higher legume prices, the share of cropland allocated to the cassava-pigeonpea intercrop (T4) increases from an average of 74 percent to 85 percent across the three years.

For scenario 6, which models the impact for farming households of jointly implementing all of the policy alternatives considered in scenarios 2 to 5, we observe similar optimal cropping patterns to those found in scenario 5. However, the percentage of land allocated to the cassava-pigeonpea intercrop (T4) is relatively higher in this scenario compared to scenario 5—the share of cropland allocated to T4 is increased by about 6 percentage points on average. This implies for the NL zone that when land, labor, yield, and output market constraints are relaxed, the farm household may take on sustainable intensification practices such as cassava-pigeonpea (T4) and maize- pigeonpea (T3) intercropping. In addition, that cassava-pigeonpea intercropping dominates the maize intercrops in scenario 6 is likely due to cassava and pigeonpea being more suited to the climatic conditions of the NL zone than maize. Farming households in NL likely are reducing the weather-related production risks they face by planting cassava and pigeonpea as intercrops rather than planting maize.

5.3 Central Mid-altitude Plateau zone

For the CMAP model, we considered maize, groundnut, and bean. The cropping systems we analyzed were maize (T1M), groundnut (T1G), and bean (T1B) in pure stands; a maize-bean intercrop (T2); a maize-groundnut intercrop (T3); and a bean-groundnut intercrop (T4). Key findings from the CMAP model scenario results are presented in Table 5.3. The agroecological conditions in CMAP are like those for NMAP. Consequently, the results for the CMAP zone are not very different from the NMAP results (Table 5.1)

Table 5.3 Optimal cropping plan—Central Mid-altitude Plateau zone

	Year 1		Year 2		Year 3	
Optimal mix	Land allocation, avg., acres	Share, %	Land allocation, avg., acres	Share, %	Land allocation, avg., acres	Share, %
Baseline scenario (1)					*Landholding, avg.: 2.00 acres*	
T1M	1.460	73	1.620	81	1.600	80
T3	0.540	27	0.380	19	0.400	20
Labor policy (doubling of available labor) scenario (2)					*Landholding, avg.: 2.00 acres*	
T1M	1.042	52	0.780	39	0.680	34
T3	0.958	48	1.220	61	1.320	66
Land policy (20 percent more cropland) scenario (3)					*Landholding, avg.: 2.40 acres*	
T1M	0.984	41	0.864	36	0.792	33
T3	1.416	59	1.536	64	1.608	67
Input market policy (legume yields doubled) scenario (4)					*Landholding, avg.: 2.00 acres*	
T2	0.600	30	0.500	25	0.420	21
T3	1.400	70	1.500	75	1.580	79
Output market policy (legume prices doubled) scenario (5)					*Landholding, avg.: 2.00 acres*	
T2	0.700	35	0.840	42	0.780	39
T3	1.300	65	1.160	58	1.220	61
Unconstrained (all four modifications jointly) scenario (6)					*Landholding, avg.: 2.40 acres*	
T3	0.720	30	1.176	49	0.720	30
T4	1.680	70	1.224	51	1.680	70

Source: Author.
Note: Cropping systems assessed were maize (T1M), groundnut (T1G), and bean (T1B) in pure stands; maize-bean intercrop (T2); maize-groundnut intercrop (T3), and double-up bean-groundnut intercrop (T4).

As with the NMAP results, the optimal cropping strategy under baseline conditions in the CMAP zone is subsistence cropping with a focus on maize in pure stand (T1M) and some intercropping of maize and groundnut (T3). In scenarios 2 and 3, we see increased use of maize-groundnut intercropping (T3), with an increasing share of cropland being dedicated to this cropping system over time, with a parallel reduction in the cropland planted to maize in pure stand (T1M).

The biggest distinctions in the results between CMAP and NMAP zones are, first, that improved access to labor (scenario 2) pushes the farm household to intercrop more in the NMAP than in the CMAP zone. This likely is because labor is a relatively less binding constraint on crop production in the CMAP zone. Secondly, when the landholding of the farming household is increased (scenario 3), we see somewhat greater employment of maize-groundnut intercropping (T3) in CMAP than in NMAP. Land seems to be a more binding constraint on the crop production of farming households in the CMAP zone than is labor.

For scenarios 4 to 5 in CMAP, we observe similar optimal cropping patterns to those seen for NMAP—relative to the baseline scenario, the optimal cropping system mix is to incorporate more legumes in the cropping system with the maize-bean intercrop (T2) and maize-groundnut intercrop (T3) dominating the mix. However, the impact of the output market policy (scenario 5) results in a share of cropland being put to the double-up legume intercrop (T4) in NMAP. This is not seen in CMAP. These results underscore the importance of considering spatial variations when analyzing patterns of adoption of sustainable agricultural intensification practices—we observe that the optimal cropping patterns associated with the different policy changes vary across NMAP and CMAP regardless of their similarities in crop suitability.

However, the results for scenario 6 in NMAP and CMAP are similar—double-up intercropping of bean and groundnut dominates the crop mix in both AEZs. Lastly, in terms of legume variations, farming households in CMAP are more likely to produce groundnut than bean, while farming households in NMAP tend to do the opposite.

5.4 Central and Southern Lakeshore zone

For the CSL model, we considered maize, groundnut, and pigeonpea. The cropping systems we analyzed were maize (T1M), groundnut (T1G), and pigeonpea (T1P) in pure stands; a maize-pigeonpea intercrop (T2); a maize-groundnut intercrop (T3), and a double-up groundnut-pigeonpea intercrop (T4). Key findings from the CSL model scenario results are presented in Table 5.4.

For the baseline scenario (1), the optimal production plan for a farming household in CSL is to allocate considerably more land to the maize-pigeonpea intercrop (T2) in the first year of the three year planning period, before reverting to maize in pure stand as the main cropping system in years two and three. It is unclear what might cause this shift in cropping pattern, although maize in pure stand is reflective of cropping patterns as now observed in the CSL AEZ.

The labor policy scenario (2) shows an optimal cropping pattern for all three years similar to that of the years two and three of the baseline scenario (1). However, the land policy scenario (3) in CSL results in a significantly greater allocation of land to cropping systems that include legumes. This likely is because land, rather than labor, is a relatively more binding constraint on crop production in CSL.

Table 5.4 Optimal cropping plan—Central and Southern Lakeshore zone

	Year 1		Year 2		Year 3	
Optimal mix	Land allocation, avg., acres	Share, %	Land allocation, avg., acres	Share, %	Land allocation, avg., acres	Share, %
Baseline scenario (1)					*Landholding, avg.: 1.80 acres*	
T1M	1.368	24	1.044	58	1.152	64
T2	0.432	76	0.756	42	0.648	36
Labor policy (doubling of available labor) scenario (2)					*Landholding, avg.: 1.80 acres*	
T1M	1.098	61	0.918	51	1.080	60
T2	0.702	39	0.882	49	0.720	40
Land policy (20 percent more cropland) scenario (3)					*Landholding, avg.: 2.16 acres*	
T1M	0.281	13	0.410	19	0.302	14
T2	1.188	55	1.274	59	1.015	47
T3	0.691	32	0.475	22	0.842	39
Input market policy (legume yields doubled) scenario (4)					*Landholding, avg.: 1.80 acres*	
T1M	0.162	9	0.144	8	0.126	8
T2	1.422	79	1.530	85	1.314	81
T3	0.216	12	0.126	7	0.186	11
Output market policy (legume prices doubled) scenario (5)					*Landholding, avg.: 1.80 acres*	
T1M	0.108	6	0.126	7	0.126	7
T2	1.170	65	1.044	58	1.098	61
T3	0.522	29	0.630	35	0.576	32
Unconstrained (all four modifications jointly) scenario (6)					*Landholding, avg.: 2.16 acres*	
T2	0.670	31	0.734	34	0.799	37
T3	0.238	11	0.281	13	0.238	11
T4	1.253	58	1.145	54	1.123	52

Source: Author.
Note: Cropping systems assessed were maize (T1M), groundnut (T1G), and pigeonpea (T1P) in pure stands; maize-pigeonpea intercrop (T2); maize-groundnut intercrop (T3), and double-up groundnut-pigeonpea intercrop (T4).

The results for the CSL AEZ for scenarios 4 and 5 are relatively similar—relative to the baseline, with higher legume yields and higher legume prices, the optimal cropping patterns from smallholder farming households is to reduce the land allocated to maize in pure stand and increase production of both pigeonpea and groundnut as intercrops with maize. With increased legume yields through farmers having better access to improved legume seed (scenario 4), a greater share of cropland is optimally allocated to the maize-pigeonpea intercrop than is the case when higher legume prices can be obtained (scenario 5). The importance of the maize-groundnut intercrop increases under scenario 5 relative to scenario 4, even though the allocation of land to the maize-pigeonpea intercrop still dominates.

For the unconstrained scenario (6), the optimal cropping plan increases legume production, with the double-up groundnut-pigeonpea intercrop system being the dominant cropping system. Under the unconstrained scenario, no production of maize in pure stand is recommended.

Although NL and CSL have similar climatic conditions, from our spatial analysis, we learn that the crop suitability for these two zones differs. This results in some variations in adoption patterns of cereal-legume intercropping, as well as increased cropping of cassava in NL. While both zones have a subsistence cropping system in the baseline scenario, CSL has an advantage over NL as it has more legumes integrated at baseline, likely due to having more legumes options adapted for the zone (groundnut and pigeonpea) compared to NL, which only has pigeonpea. Similarly, when the market policies (Scenario 4 and 5) are implemented in these zones, the impact of those policies on the optimal production plan for farming households differ in each zone. For instance, although both the input and output market policies increase the land area allocated to cereal-legume intercropping in the lakeshore zones, the market policies have a more substantial impact in NL than in CSL. This could be because the legume input and output market constraints may be more binding in NL compared to CSL. This difference would contribute to CSL having a greater area cropped to legumes at the baseline compared to NL.

5.5 Southern Mid-altitude Plateau zone

For the SMAP model, we considered maize, groundnut, and pigeonpea. The cropping systems we analyzed were maize (T1M), groundnut (T1G), and pigeonpea (T1P) in pure stands; a maize-pigeonpea intercrop (T2); a maize-groundnut intercrop (T3), and a double-up groundnut-pigeonpea intercrop (T4). Key findings from the SMAP model scenario results are presented in Table 5.5.

Table 5.5 Optimal cropping plan—Southern Mid-altitude Plateau zone

	Year 1		Year 2		Year 3	
Optimal mix	Land allocation, avg., acres	Share, %	Land allocation, avg., acres	Share, %	Land allocation, avg., acres	Share, %
Baseline scenario (1)						*Landholding, avg.: 1.50 acres*
T1M	0.630	42	0.615	41	0.720	48
T2	0.870	58	0.885	59	0.780	52
Labor policy (doubling of available labor) scenario (2)						*Landholding, avg.: 1.50 acres*
T1M	0.585	39	0.570	38	0.540	36
T2	0.915	61	0.930	62	0.960	64
Land policy (20 percent more cropland) scenario (3)						*Landholding, avg.: 1.80 acres*
T1M	0.468	26	0.558	31	0.486	27
T2	1.332	74	1.242	69	1.314	73
Input market policy (legume yields doubled) scenario (4)						*Landholding, avg.: 1.50 acres*
T2	1.050	70	0.825	55	1.185	79
T3	0.450	30	0.675	45	0.315	21
Output market policy (legume prices doubled) scenario (5)						*Landholding, avg.: 1.50 acres*
T2	1.035	69	0.885	59	0.990	66
T4	0.465	31	0.615	41	0.510	34
Unconstrained (all four modifications jointly) scenario (6)						*Landholding, avg.: 1.80 acres*
T2	0.450	25	0.558	31	0.468	26
T3	0.342	19	0.378	21	0.342	19
T4	1.008	54	0.864	48	0.990	55

Source: Author.
Note: Cropping systems assessed were maize (T1M), groundnut (T1G), and pigeonpea (T1P) in pure stands; maize-pigeonpea intercrop (T2); maize-groundnut intercrop (T3), and double-up groundnut-pigeonpea intercrop (T4).

With pigeonpea instead of bean, the crops considered for this zone differ from those of the NMAP and CMAP zones, even though the agroecological conditions across the three AEZs are similar. However, SMAP has a higher population density than the other two mid-altitude plateau zones. The baseline results show similar cropping patterns across the three zones—maize grown in pure stand and a maize-legume intercrop. However, the optimal cropping system mix for SMAP shows a much smaller share of cropland allocated to maize grown in pure stand—only about 45 percent on average versus over 75 percent in the other two mid-altitude plateau zones.

With increased access to labor (scenario 2), the optimal cropping plan is for farming households to increase the share of land they allocate to the maize-pigeonpea intercrop cropping system relative to the baseline scenario. However, the increase in the share of land allocated to intercropping in SMAP is much less than the increase in land allocated to intercropping in both NMAP and CMAP under scenario 2. This likely reflects labor being less of a constraint on crop production in SMAP than in the other two zones.

With an increase in cropland (scenario 3), a similar pattern is seen as with increase in labor, although with a somewhat higher share of cropland allocated to the maize-pigeonpea intercrop in SMAP than was the case in the labor scenario (2). Across the three mid-altitude plateau zones, a somewhat larger share of land is allocated to the maize-legume intercropping in SMAP under scenario 3 than is the case for NMAP and CMAP. This likely reflects land being a relatively more binding constraint to crop production in SMAP than in NMAP and CMAP.

For the two market scenarios (4 and 5) in SMAP, the optimal cropping patterns are similar to those obtained for CMAP and NMAP for the two scenarios—maize grown in pure stand drops out of the optimal cropping pattern being replaced by maize-legume intercrops or double-up legume intercrops. There is little difference between the two market scenarios in terms of how they affect the optimal cropping pattern for farming households in SMAP.

For the unconstrained scenario (6), the optimal cropping plan shows an increase in legume production with all three intercrop systems being employed and no maize in pure stand. However, of particular note is that about half of a farming household's cropland should be optimally dedicated to the double-up groundnut-pigeonpea intercrop. This intercrop, which does not include maize, is the dominant cropping system in SMAP when all constraints are eased.

5.6 Lower Shire Valley zone

For the LSV model, we considered sorghum, groundnut, and pigeonpea. The cropping systems we analyzed were sorghum (T1S), groundnut (T1G), and pigeonpea (T1P) in pure stands; a sorghum-pigeonpea intercrop (T2); a sorghum-groundnut intercrop (T3), and a double-up groundnut-pigeonpea intercrop (T4). Key findings from the LSV model scenario results are presented in Table 5.6.

The optimal production plan for farming households in LSV under baseline conditions is to allocate just over three-quarters of their land to sorghum in pure stand and the rest to an intercrop of sorghum and pigeonpea. The intercrop is quite well-suited for LSV as the frequent dry spells and droughts in the AEZ push farming households to intercrop drought-resistant crops, such as sorghum and pigeonpea, as a form of diversification to reduce risks to production. Another reason for farming households to integrate legumes into their farming is that legumes have multiple uses. Notably, pigeonpea stover can be used as animal feed—across Malawi, livestock population densities are highest in the LSV zone (NSO 2019).[4]

Where household labor constraints are relaxed by doubling the available family labor (scenario 2), the optimal cropping strategy for farming households in LSV is to increase the cropland allocated to sorghum-pigeonpea intercrop by about 200 percent relative to the baseline. This sharp increase in the share of land allocated to this intercrop reflects how farmers might obtain maximum productivity from their limited land by intercropping. However, intercropping requires more labor than growing sorghum in pure stand.

[4] The LSV zone has the highest livestock densities nationally—32 goats/km^2, 5 pigs/km^2, 17 cattle/km^2, and 72 chickens/km^2 (NSO 2019).

Table 5.6 Optimal cropping plan—Lower Shire Valley zone

Optimal mix	Year 1 Land allocation, avg., acres	Year 1 Share, %	Year 2 Land allocation, avg., acres	Year 2 Share, %	Year 3 Land allocation, avg., acres	Year 3 Share, %
Baseline scenario (1)						*Landholding, avg.: 1.20 acres*
T1S	0.924	77	0.996	83	0.972	81
T2	0.276	23	0.204	17	0.228	19
Labor policy (doubling of available labor) scenario (2)						*Landholding, avg.: 1.20 acres*
T1S	0.396	33	0.348	29	0.432	36
T2	0.804	67	0.852	71	0.768	64
Land policy (20 percent more cropland) scenario (3)						*Landholding, avg.: 1.44 acres*
T1S	0.187	13	0.490	34	0.965	54
T2	1.253	87	0.950	66	0.835	46
Input market policy (legume yields doubled) scenario (4)						*Landholding, avg.: 1.20 acres*
T2	0.840	70	0.660	55	0.948	79
T3	0.360	30	0.540	45	0.252	21
Output market policy (legume prices doubled) scenario (5)						*Landholding, avg.: 1.20 acres*
T2	0.828	69	0.684	57	0.792	66
T4	0.372	31	0.516	43	0.408	34
Unconstrained (all four modifications jointly) scenario (6)						*Landholding, avg.: 1.44 acres*
T2	0.475	33	0.562	39	0.533	37
T4	0.965	67	0.878	61	0.907	63

Source: Author.
Note: Cropping systems assessed were sorghum (T1S), groundnut (T1G), and pigeonpea (T1P) in pure stands; sorghum-pigeonpea intercrop (T2); sorghum-groundnut intercrop (T3), and double-up groundnut-pigeonpea intercrop (T4).

In scenario 3, where the land constraints are relaxed, we also observe a similar change in the optimal technology mix where LSV farming households increase the land allocated to the sorghum-pigeon intercropping from 23 percent in the baseline to 87 percent in the first year of the three-year planning period. Removal of the land constraints influences farming households to allocate relatively more land to the intercrops compared to the scenario in which labor constraints are reduced (scenario 2). Land may be a more constraining factor to crop production in LSV than labor, given the relatively high population density for the zone of about 250 people per square kilometer—a similar population density to SMAP.

The scenario of increased legume yields (4) results in the optimal cropping pattern for LSV farming households shifting away from any sorghum grown in pure stand to a combination of sorghum-groundnut and sorghum-pigeonpea intercrops. Higher legume prices in scenario 5 result in a similar shift in cropping patterns as in scenario 4 away from sorghum grown in pure stand. However, rather than allocating land to a sorghum-groundnut intercrop, as in scenario 4, the optimal cropping strategy in scenario 5 is for farming households to replace the sorghum-groundnut intercrop with the double-up groundnut-pigeonpea intercrop to expand their legume production while reducing their sorghum production. In both scenarios, about two-thirds of the cropland of farming households is optimally devoted to a sorghum-pigeonpea intercrop.

In scenario 6 in which farming households do not face any resource or market constraints, we observe a similar optimal cropping pattern to that for scenario 5 with only the sorghum-pigeonpea intercrop and double-up groundnut-pigeonpea intercrop in the optimal production plan. However, relative to scenario 5, farming households in LSV should increase the land they allocate to the double-up groundnut-pigeonpea intercrop from about one-third of their cropland to about two-thirds under this unconstrained scenario.

6 CONCLUSIONS

The spatial analysis we conduct through this study shows the importance of considering location-specific variations in analyzing factors that influence the adoption of sustainable agricultural intensification methods. Although varying constraints on land, labor, and access to legume markets influence farming households' cropping system choices, the level of impact on farming households' decisions varies across AEZs. We find that farming households adopt a subsistence approach focused on staple food production in the baseline scenario across all zones. However, the level of subsistence and the type of crops retained under baseline conditions depend on crop suitability in an AEZ. For example, we observed that maize dominated in the NMAP and CMAP zones, while cassava was more prominent than maize in the NL zone.

Our results highlight the significance of land constraints across all regions, with SMAP being the most land constrained zone. Increasing the land available to farming households by 20 percent (scenario 3) influences households in the SMAP zone to intercrop more relative to other zones. This likely is due to the relatively more binding land constraint within SMAP relative to the other zones. Our results suggest that land constraints have a pronounced effect on the optimal production plans and the choice farming households make of the cropping systems they will use, especially in SMAP. This underscores the importance of considering land constraints when designing agricultural interventions aimed at supporting sustainable farming practices in Malawi, particularly in the SMAP AEZ.

Our analysis also highlights the importance of considering variations in access to both agricultural input and output markets. Improving the legume productivity of farming households through increasing their access to input markets offering improved legume seed (scenario 4) and boosting the prices they receive for the legumes they produce through improving their access to higher-value output markets (scenario 5) affects the decisions farming household make how whether and, if so, how to integrate legumes in their cropping systems. However, the level of legume integration varies across zones depending on the access farming households in a zone have to strong agricultural input and output markets. Farming households in AEZs that are in closer proximity to cities, where more dealers in agricultural products, agri-processors, and agricultural exporters can be found, are more likely to benefit from improvements in agricultural input and output markets. For example, although NMAP, CMAP, and SMAP are similar in terms of agroecological conditions, the input and output market scenarios (4 and 5) show different results across these AEZs. Farming households in NMAP, which is the most distant zone from urban centers, were more impacted by the two market scenarios relative to CMAP and SMAP. Location matters when analyzing how factors such as land, labor, and access to input and output markets influence smallholder farming households' adoption of sustainable agricultural intensification practices—particularly cereal-legume intercropping—in Malawi.

Our analysis shows that out of the different constraints that farming households face across regions, constraints on land and market access mattered the most in the farming households' decision process. Our study highlights the significance of land constraints across all regions, with SMAP being the most land-constrained zone. We also find that access to input and output markets plays a pivotal role in shaping the adoption of cereal-legume intercropping systems among farming households across all agroecological zones. Of particular interest, our analysis highlights how the level of legume integration varies across zones, with improved access to input markets offering improved legume seeds having a substantial impact on farming households' adoption of legume-based cropping patterns across all regions. NMAP is the most affected zone under this scenario (4).

This spatial analysis, therefore, serves as a valuable resource for researchers, stakeholders, and policymakers considering policies to accelerate the adoption by smallholder farming households in Malawi of sustainable agricultural intensification practices. The results of our modeling offer insights for developing targeted interventions and strategies to support the increased adoption of such practices. By recognizing diversity in adoption patterns and the influence of location-specific constraints, stakeholders can design context-specific strategies to promote sustainable agricultural intensification and enhance agricultural productivity by smallholder farming households. Some key policy recommendations from the study include:

- Implementing programs to improve agricultural land management;
- Increasing the access of smallholder farming households to agricultural markets, especially to input markets from which they can obtain improved legume seeds;
- Developing market information systems to benefit both farmers and crop traders; and
- Providing farming households with contingent lines of credit to enable them to obtain agricultural inputs.

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ACKNOWLEDGMENTS

Funding for this work was provided by Developing Smart Innovation through Research in Agriculture (DeSIRA) project. This publication has been prepared as an output of DeSIRA and has not been independently peer reviewed. Any opinions expressed here belong to the author and are not necessarily representative of or endorsed by IFPRI.

The Malawi Strategy Support Program (MaSSP) is managed by the International Food Policy Research Institute (IFPRI) and is financially supported by USAID, the Government of Flanders, Irish Embassy, and FCDO. This publication has been prepared as an output of MaSSP and has not been independently peer reviewed. Any opinions expressed here belong to the author(s) and are not necessarily representative of or endorsed by IFPRI, CGIAR, the United States Government, or the Government of Flanders.

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