Nudging smallholders to integrate more legumes into their farms - a farm model quantification

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1 Introduction and objective

The increase in both income and food security of smallholder farmers in low-income countries is challenged by unpredictable weather and economic changes. Protecting the ecosystems that support farm long-term productivity, is one additional constraint, as smallholder farmers often have to prioritize short-term goals over long-term environmental concerns. Ensuring the sustainable development of smallholder agriculture, meaning meeting current human needs without jeopardizing the ability of future generations to meet their own, is challenged by low productivity of annual cropping systems, that limits substantial increase in income and food security Giller et al. (2021). Agroecological intensification is portrayed as a promising way to reconcile increase in productivity and environmental preservation. Yet, its implementation is limited by the availability of workforce, and can generate trade-offs between long-term environmental benefits and short-term farmers' goals (food security with staple crop, cash crop with secured market).

Integrating more legume crop into farming systems is one typical pathway through agroecological intensification. Legumes ensure key provision ecosystem services, as well as regulating services when it comes to climate, pest and diseases (Ditzler et al., 2021). Legume production contributes to the provision of quality food and feed. Including legumes into cropping system brings nitrogen through biological fixation. This limits the need to produce and apply mineral fertiliser, and the associated greenhouse gases emission (Cai et al., 2018). Rotating cereals with legumes breaks the growing cycle of weeds, pest, and disease. This contributes to reduce the need for pesticides on cereal (Ripoche et al., 2021). However, in land constrained environments of global South, integrating more legume in sole cropping means replacing currently grown staple or cash crops by legume crops or cultivating a fallow land. Therefore, including more legume in the farming systems competes land, and may as well compete for labour. Subsidising legume production, for the ecosystem services they deliver, may be one option to increase their share in farm cropland. However, effects of this incentive on land allocation may differ across farm types and site, depending on climate and socio-economic context. The productivity gap between legume and cereal can be lower in more sub-humid climates, or the level of market integration of farmers can change the trade-offs between the short-term and long-term goals of farmers.

In this study, we want to leverage existing detailed farm data in four contrasting case studies in the Global South to explore the following questions:

- Given current market conditions, why is legume share of cropland low in most farmers' cropland? What constraints their flexibility to expand legume cultivation?
- What amount of subsidy for legume cultivation is required to lift up the share of legume in the cropland, in order to bring additional ecosystem services, without compromising farmers current objectives?
- How does the subsidy amount vary per farm type and across sites in smallholder context?

Methodological considerations

Whole-farm models can be used to assess the effects of current farm-level constraints (workforce, cash, food security) on land/activities allocation and to *ex ante* assess the effects of financial incentives on this allocation. Whole-farm models are simplified versions of the farming systems and all their sub-components (cropping systems, livestocks systems, household strategies). Using these models allow assessing (i) how financial incentives release economic constraints, (ii) how the new practice that is incentivized can increase farm performance. van Wijk et al. (2014) identified 3 main categories of whole farm models combining biophysical and socio-economic aspects, based on a review of 126 farm household models.

The first category is composed of dynamic simulation models, based on rule-based management and different levels of complexity to describe the biophysical processes. These models (e.g., GAMEDE (Vayssieres et al., 2009); NUANCES-FARMSIM (van Wijk et al., 2009)) are built to answer "what if" questions, i.e. analyze consequences at farm-level of a change on a sub-component of the farm model. These simulation models are sometimes combined with other types of models, as Berre et al. (2015) did with the GAMEDE model to valorize the potential of simulation and optimization models. The second type of model are multi-agent models that focus on tactical and strategical decision making (by farmers or other stakeholders) and its implication on the farming systems. These models (e.g. Valbuena et al. (2010) Valbuena et al. (2010); Berre et al. (2021) can be spatially explicit and can explore trade-offs within the farming system or even at landscape scale. The third category are Mathematical Programming (MP) models based on systems of equations, classically based on linear programming but can also be more dynamic or recursive. Based on a set of equations, these models help answer "how to" questions and help identify the best solution for an objective function (e.g., income maximization) under a set of constraints. If multiple goals, or multiple criteria objective are frequently used, the most common objective function is related to the economic situation of the farm (e.g. maximize discretionary income (Jourdain et al., 2014); maximize total net income (Naudin et al., 2015)). In these models, decision making is based on optimization and most biophysical processes and exogeneous data (market, climate) are based on technical coefficients. The approach based on optimization to maximize income is particularly suited for the context of smallholder farms of the Global South, where day-to-day considerations matters. For instance, in sub-Saharan Africa, most farms operate below poverty line (including home consumption), and each worker often supports multiple dependents. In such contexts, any agroecological alternatives that reduce short-term income is not desirable, even-if it could lead to an increase in income on the longer term. Models based on mathematical programming have been used to assess ex ante the potential of a subsidy to compensate farmers. For instance, Wang and Nuppenau (2021) measured the amount of a subsidy that could compensate farmers to stop deforestation. Affholder et al. (2010) calculated the amount of subsidy needed to compensate the short-term extra-cost (inputs and labor) generated by an alternative agricultural practice (direct-seeding mulch). The afore-mentioned study was based on single site analysis.

2 Methods

2.1 Site description

We selected six regions across four countries, representing contrasted agroecological environments and farming dynamics (Table 1). The average annual rainfall across our study sites ranges from 500 mm to 1400 mm, while average farm sizes vary between 1 ha and 8 ha. Overall, households are low resource endowed and live under the $2.15 a day extreme poverty line. All farms operate as semi-subsistence farms, with varying degrees of market integration and farmland size depending on the region. Smallest farms are found in Zimbabwe where farmers mainly crop for their own consumption with low connection with the market. In Senegal and Burkina Faso, farmland size is larger, but as a result of larger families. In southern Burkina Faso and Senegal, farms are more market-oriented, growing cash crops such as groundnuts in Senegal and cotton and soybeans in southern Burkina Faso. In Laos, maize serves as the primary cash crop, entirely exported to Vietnam, while rice is cultivated in lowland areas for family consumption.

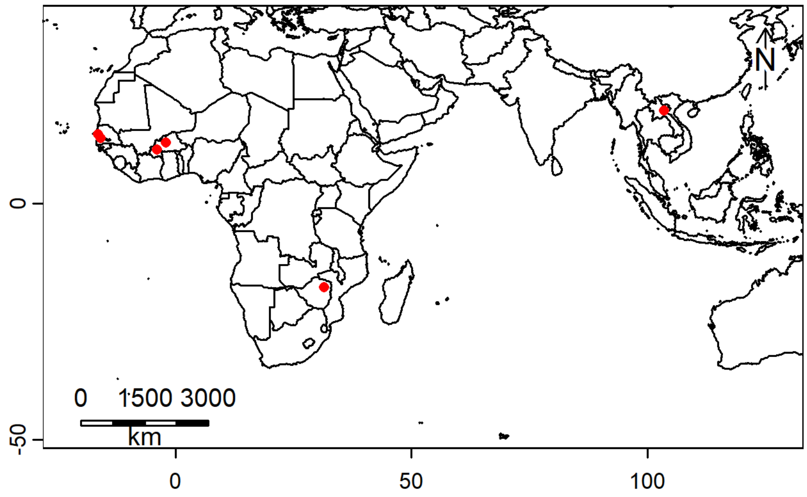

Figure 1: Location (red dots) of the study sites in Africa and south-East Asia

Table 1: Characteristics of the six study sites, sources: (Lairez et al., 2023); (Lairez et al., under review); (Ricome et al., 2017);(Gérard et al., 2020); (Manyanga et al., 2024).

	Site					
General information						
Country	Burkina Faso	Burkina Faso	Lao PDR	Senegal	Senegal	Zimbabwe
Region	Nord	Hauts-Bassins	Xieng Khouang	Sine	Saloum	Mashonaland East
Main city	Arbollé	Léna	Muang Kham	Niakhar	Nioro du Rip	Murewa
Latitude	12°50'N	11°18'N	19°38′N	14°28’N	13°44’N	17°48'S
Longitude	2°02'W	3°53W	103°33E	16°24’W	15°46W	31°36'E

Elevation (m)	330	340	1300	6	28	1370
Climate	semi-arid	semi-arid	humid subtropical	semi-arid	semi-arid	humid subtropical
Mean temperature (°C)	28.3	28	22	28	28	20
Annual rainfall (mm)	500	750	1400	500	700	900
Farming systems						
Average household size	11.7	9.7	5.35	13	15.0	4
Average cropped land (ha)	3.7	9.25	3.7	3.5	6.5	1
Main cereal crops	sorghum, millet	maize	maize, rice	millet	millet	maize
Main cash crops	groundnut, cowpea	cotton, soybean	maize	groundnut, maize	groundnut, maize	maize, tobacco
Presence of legume	medium	medium	none	medium	medium	low
Horticulture	none	mango, cashew nut	banana	watermelon	tomato, carrot	tomato, greens, butternut, cabbage, onions
Livestock rearing	free grazing	free grazing	free/pasture grazing, stall feeding	free grazing	free grazing, short-term fattening	free grazing
Mechanization	none	low	high	low	low	low
Off-farm opportunities	low	medium	high	medium	medium	medium

2.2 General approach for farm modelling

The general approach was to build a multi-site farm model designed to simulate the strategic decisions of farmers who would optimize their farm activities under a set of constraints (land availability, food security, family workforce) and toward a single farmer strategic objective of maximizing annual farm income (Figure 1). The model represents contrasting farm types and the key interactions between farm structure and its environment. In each site a farm typology was made, a real ‘observed’ farm per farm type was selected to be modelled, and scenarios were made introducing a subsidy to legume cropping area.

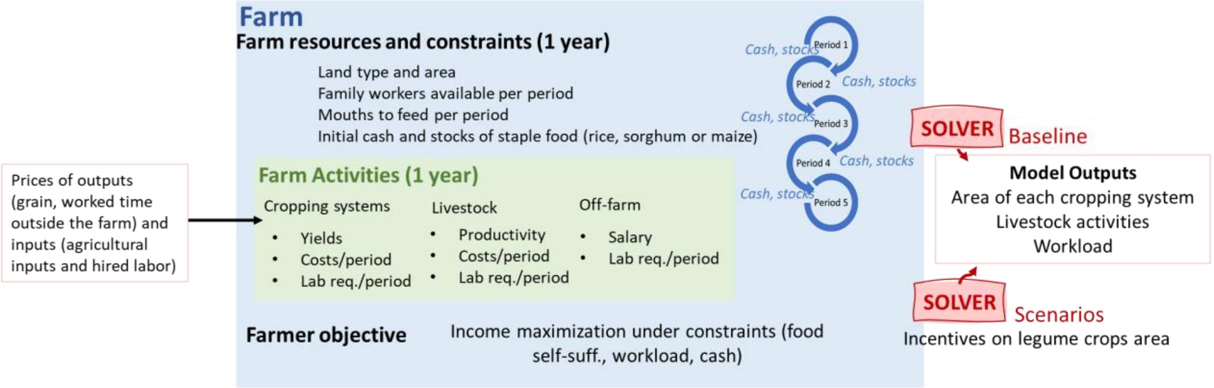

Figure 2: Description of the farm model built and used in this study

The model works based on a description of farm structure. Inputs include the sets of possible activities that the simulated farms can implement in order to maximise income, under a set of specified constraints. Each farm is described by the number of available workers and mouths to feed, the size of the available land, initial cash flow and stock of grain at the start of the simulation. Additionally, each cropping and livestock system must be defined using *technical coefficients*, that include costs, productivity, and labor requirements. Prices of outputs and inputs are also needed.

2.3 Data used as input in the farm model

The data used to build the farm model comes from different surveys or pre-existing models (Lairez et al., 2024), (Ricome et al., 2017), (Manyanga et al., 2024). (Lairez et al., 2023)

Table 2: Sources of data collected for input to the farm model

	Laos	**Senegal**	**Burkina Faso**	**Zimbabwe**
Source of data for farm structure				
Source of data for farm typology	112 farms surveyed in 2017	180 farms surveyed in 2013	215 farms surveyed in 2022	248 farms surveyed in 2022
Variables used for farm typology	Maize/lowland rice/dry season crops area, off-farm income, household size, herd size, equipment score	Farmland size, household size, area per worker, herd size, number of draught animals and number of migrants	Farmland size, family size, off-farm income, number of draught animals, herd size, equipment score	Family size, cropped area, TLU, agricultural and off-farm income, maize stock and consumption, assets value, input costs
Number of farms selected to be modelled	3	4	5	4
Source of data for technical coefficient				
Yield	Field monitoring (35 fields) and survey of 16 farms	Field monitoring (206 fields) and survey of 40 farms	Field monitoring (413 fields) and survey of 30 farms	Survey of 248 farms
Labor requirements	Field monitoring (35 fields) and survey of 16 farms	Survey of 180 farms	Survey of 30 farms (150 fields)	Survey of 248 farms
Costs of inputs	Survey of 16 farms	Survey of 180 farms	Survey of 30 farms	Survey of 248 farms
Source of data for selling/buying prices of crops	Survey of 16 farms	Survey of 180 farms	Survey of 30 farms	Survey of 248 farms

- In Laos and Senegal

All technical coefficient of farming activities were kept the same as defined in the study of Lairez et al. (2023) and Ricome et al., (2017). The livestock components were simplified considering only 2 types of livestock systems per site (cattle/goat roaming for Senegal and pig husbandry/cattle fed with pasture in Laos).

- In Zimbabwe and Burkina Faso

In Zimbabwe and Burkina Faso, we needed first to determine the technical coefficients of the cropping systems (yield, labour requirements, costs, etc.). This was carried out through analysis of field-level data (survey) on crop types, crop management, yields, costs, the number of workers, and the hours and periods of work of surveyed households. Labor requirement, expressed in person-days per hectare, was calculated by considering the number of workers and the duration of their interventions, assuming an 8-hour workday. 175 fields were surveyed in Burkina Faso and 450 fields in Zimbabwe (see appendix 1). For each country, we analyzed (i) total labor requirement by crop, (ii) labor requirement per operation (land preparation, sowing, weeding, harvesting, etc.) whatever the crops, and (iii) labor requirement per operations for each crop.

Yields were calculated based on farmers' field monitoring, averaged per cropping system depending on the level of inputs (fertiliser, pesticides). The average recorded prices of inputs per studied areas was expressed in local currency. Agricultural input prices were standardized to the same units (e.g. FCFA/kilogram for fertilizers and seeds, FCFA/liter for pesticides).

2.4 Farm model description

Potential farming activities were the current cropping systems as described in Table 3.

Table 3: Cropping systems considered in the farm model in the different sites

Zone	**Crop name**	**cropping system**	**Min fert (kg N/ha)**	**Org fert (kg N/ha)**	**Pest management**
Burkina South	cotton	non-edible cash crop high input	50	40,5	insecticide + herbicide
Burkina South	maize	rainfed cereal - intensified	60	60	insecticide + herbicide
Burkina South	maize	rainfed cereal - low -input	0	60	herbicide
Burkina South	groundnut	rainfed legume - low input	0	0	none
Burkina South	soybean	rainfed legume - low input	0	0	none
Burkina South	groundnut	rainfed legume - medium input	0	0	herbicide
Burkina South	soybean	rainfed legume - medium input	0	0	insecticide + herbicide
Laos	rice	irrigated cereal - intensified	40	100,5	herbicide + insecticide
Laos	rice	irrigated cereal - low input	8	139,5	none
Laos	maize	rainfed cereal - intensified	15	0	herbicide
Laos	brachiarria	pasture	0	0	none
Laos	soybean	rainfed legume - med input	0	0	herbicide
North Burkina	sesame	non-edible cash crop low input	0	0	none
North Burkina	sorghum	rainfed cereal - low -input	0	30	none
North Burkina	cowpea	rainfed legume - low input	0	0	none
North Burkina	groundnut	rainfed legume - low input	0	0	none

North Burkina	cowpea	rainfed legume - medium input	14	0	pesticide
Senegal	maize	rainfed cereal - low -input	6	0	none
Senegal	millet	rainfed cereal - low -input	0	0	none
Senegal	groundnut	rainfed legume - low input	0	0	none
Senegal	groundnut	rainfed legume - medium input	9	60	none
Senegal	millet	rainfed cereal - med-input	0	20	none
Senegal	maize	rainfed cereal - med -input	200	60	none
Zimbabwe	tobacco	non-edible cash crop high input	80	0	none
Zimbabwe	tobacco	non-edible cash crop low input	0	0	none
Zimbabwe	maize	rainfed cereal - intensified	80	60	none
Zimbabwe	maize	rainfed cereal - low -input	0	0	none
Zimbabwe	groundnut	rainfed legume - low input	0	0	none

The farm model equations are presented in Table 4. The model was designed to simulate the choices of farmers, especially decisions on their crop choice, crop management strategy (manure, fertilizer, pesticide), animal production strategy, and family consumption. The model was implemented in the GAMS software (version 47.3). The single goal of maximizing one-year farm income was considered in the model. We considered several constraints applied to five time periods (or six for Senegal) in which a year was split: land, labour, cash, and staple food needs. The model was designed to consider distinct simulations for 16 farms. Each farm was characterized by the arable land available in the different land types, its household size and composition (representing mouths to feed and labour force available), initial cash and cereal stock available for consumption at the beginning of the year.

Initial cash at the beginning of first period was set as the sum of the total inputs costs for observed cropping and livestock systems, plus the sum over the year of the minimum daily expense per household. Initial amount of crop grains at the beginning of first period was set to the total quantity of product consumed by household over the first two periods (the third period is the harvest period).

Table 3: Farm model equations

Farmer objective	
Income maximization	$\text{Income} = \sum_{p,t} \text{Quantity of crop product p sold} * \text{price}$ $+\sum_{a,t} \text{Quantity of animals a sold} * \text{price}$ $+\sum_{t} \text{Days of off} - \text{farm} * \text{daily wage}$ $+\sum_{leg} \text{Area under legume crops} * \text{subsidy}$ $-\sum_{a,t} \text{Animal costs} * \text{quantity of animals raised}$ $-\sum_{c,t} \text{Area under a cropping system c} * \text{cost inputs}$ $-\sum_{t} \text{Number of hired workers} * \text{daily wage}$ $-\sum_{p,t} \text{Quantity of crop product p bought for fam. consumption} * \text{price}$
Constraints to income maximization	

Available arable land per land type	For each land type Z, $$\sum_{c} \mathrm{X(c,z)} < \mathrm{AREA(z)}$$ X(c,z): area under crop c in a land type z AREA(z): area of land type z on the farm
Constraints for each period t	
Food security to satisfy the energy needs of the family	$\mathrm{CONSOCer(t)*valEnerCer} \geq \mathrm{*Nh(h)}$ CONSOCer(t): household cereal consumption for period t (kg DM) valEnerCer the digestible energy content of rice (kcal/kg) HEnerNeed(t): human energy need (in cal) of one person of type h according to age and gender categories over period t Nh(h): number of persons of type h on the farm
Food stock balance	INI_STOCK(p,t)+PURCH(p,t)+PROD(p,t)=FARM_CONSO(p,t)+SALES(p,t)+FINAL_STOCK(p,t) INI_STOCK(p,t): initial stock of product p at the beginning of period t (kg), PURCH(p,t): the amount of product p purchased (only rice in the model) during period t (kg) PROD (p,t): amount of product p produced on farm during period t (kg), FARM_CONSO(p,t): the consumption of product p (kg) by household members (only rice in the model) during period t, SALES(p,t): amount of product p sold during period t (kg), FINAL_STOCK(p,t): stock of product p available at the end of period t.
Labour	$$\sum_{c,z} Req_{Work\,(c,z,t)} * X(c,z) + \sum_{a} Req_{Wani\,(a,t)} * Xani(a) + \sum W\_Out(t) \leq \sum W_{In\,(t)} + \sum_{g} dispoW\,(g,t)$$ X(c,z): area under a crop c in land type z, Reqwork(c,z,t): amount of work (in days) required during period t for a crop c in a land type z, Xani(a): number of an animal unit of type a, ReqWani(a,t): amount of work (in days) required during period t for an animal unit of type a, W_out(t): number of days in a period t during which household members work off-farm, W_in(t): number of days in a period t during which household members work in-farm, dispoW(g,t): labor supply in days of men, women and others (children, elders) in each period.
Cash balance	$INI\_CASH\ (t) + \sum incomes(t) = FINAL\_CASH\ (t) + \sum expenses(t)$ INI_CASH (t): initial cash available at the beginning of a period t, Incomes (t): incomes from sales or off-farm in period t, FINAL_CASH(t): cash available at the end of a period t, Expenses(t): expenses in period t for inputs, hired labour, cereal purchases

2.5 Scenario analysis

After simulating a baseline to represent observed farms land allocation (S0), a subsidy per hectare of legume was gradually introduced (S1 to S5, from USD 50 to 250/ha of legume grown), and land allocation and workload were compared across scenarios.

3 Results

3.1 Farm typology per site and choice of farms to model

In Laos, 3 farm types were considered (Lairez et al., 2023). “Type 1 – Low resource endowment (LRE)” represented the smallest maize farms with the lowest level of resource endowment (cattle, asset, cultivated area). Maize was entirely sold for cash, and rice was produced for family consumption on a small lowland area. In the two other farm types, “Type 2 – medium resource endowment (MRE)” and “Type 3-Highest resource endowment (HRE)”, all farms had access to irrigated paddy fields. MRE farms had intermediate level of resource endowment and HRE farms were the largest maize farms (total cultivated area of 9.1 ha on average) having the highest level of resource endowment of the sample.

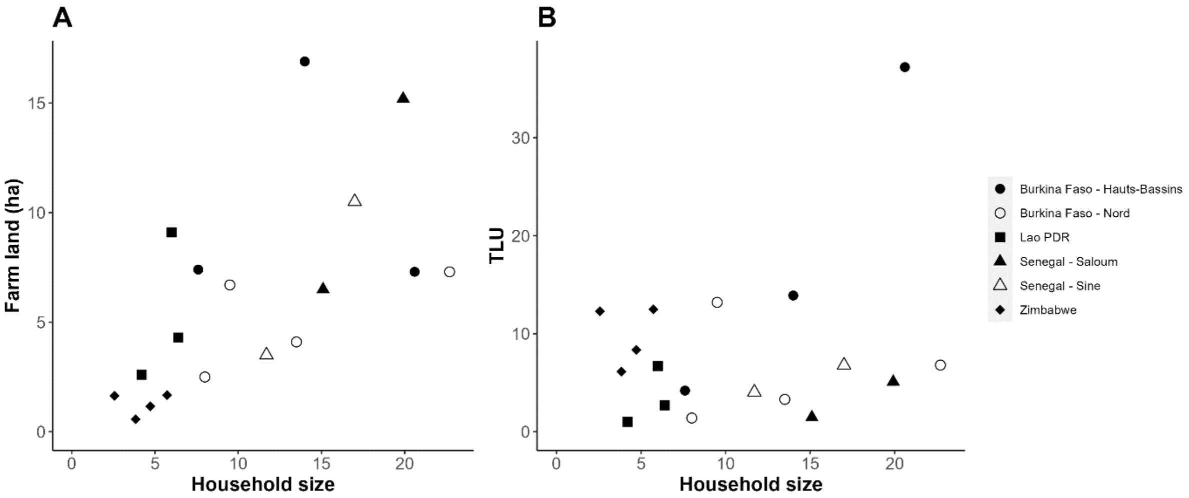

Figure 3: Diversity of farm types across the sites

In Zimbabwe, 4 farm types were considered. Type 1, identified as "Resource-Strapped Households" (RSH), comprises households with an average of four members where majority (54%) of the household members are active. This group faces extensive economic challenges and stands as the most financially vulnerable among farming households, averaging a yearly income of around USD 100 per person. Type 2 is composed of households moderately endowed with resources but lacking off-farm endeavors. It accounts for 29% of the sampled farming households, each consisting of an average household size of 5 members. The average yearly income is around USD 120 per person. Type 3 comprises of 15% of the farm households. Farmers in this cluster have access to more resources than cluster 1 and it is associated with smallest family size of 3 members with income of USD 302 per capita. Type 4 comprises of 10%

of the farm households categorized as the well-resource endowed and better off farmers getting income of USD 617 per capita.

In North Burkina Faso, 4 farm types were considered depending on their ratio farmland/household size ranging from 0.2 to 0.7 ha/person, and the presence of livestock. They all primarily focused on cultivating sorghum to meet family needs, and also sold their surplus production to obtain cash. Cereals occupied 60 to 78% of the cultivated land. In South Burkina Faso, three farm types were considered, distinguishing by their farmland size, the number of mouths to feed, and their family labor force. South Burkina is where we observed the largest cultivated area (>15 ha) across study sites. The proportion of cereals in farmland allocation in South Burkina was lower compared to North-Burkina (38-47% vs. 60-78%), as cotton was cultivated as a cash crop there. Farms in South-Burkina were more market-oriented than those in North-Burkina.

In Senegal, two types of farms were considered, both characterized by mixed crop-livestock systems primarily focused on self-sufficiency. The first type operates under greater land constraints (3.5-6.5 ha), allocating a larger share of its limited land to millet cultivation and maintaining very few livestock. In contrast, the second type has access to more land (10–15 hectares) and supports a larger family. These farms also own more livestock, though still in relatively small numbers.

3.2 Baseline crop allocation across sites

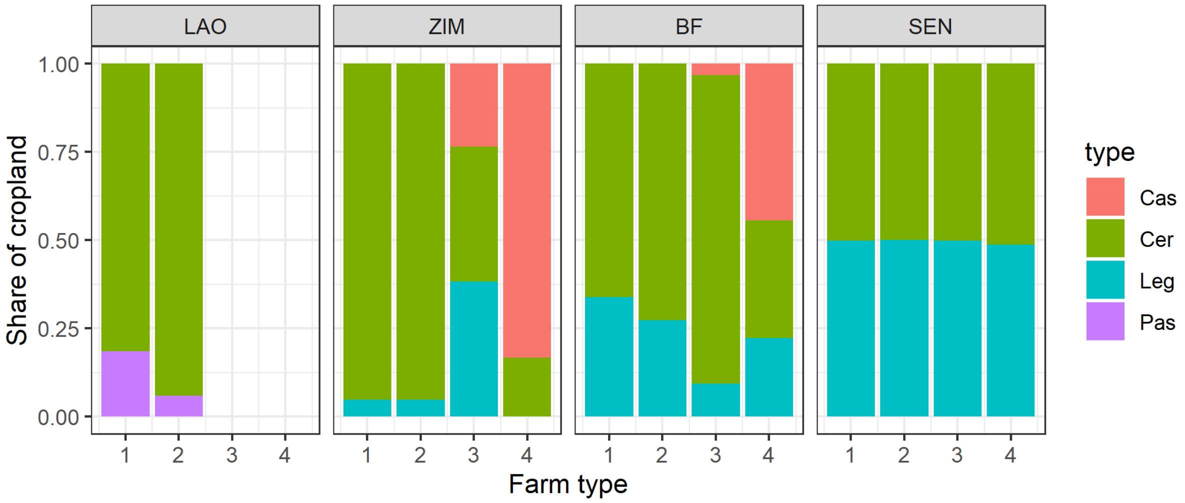

Figure 7: Current crop allocation at sites in lao PDR (LAO), Zimbabwe (Zim), Burkina Faso (BF) and Senegal (Sen) for contrasting farm types. Cas=cash crop, Cer=cereal, Leg=legume, Pas=Pasture.

Current Legume share in the cropland differs across the sites, from no legumes in LAO-PDR to substantial share in Senegal (~50%, groundnut), and intermediate share (~10-30%) in Zimbabwe and Burkina Faso (Figure 7). Cereals occupy the largest share of the cropland, except for some farm types in Zimbabwe (Type 4) where cash crop predominates.

3.3 Model calibration

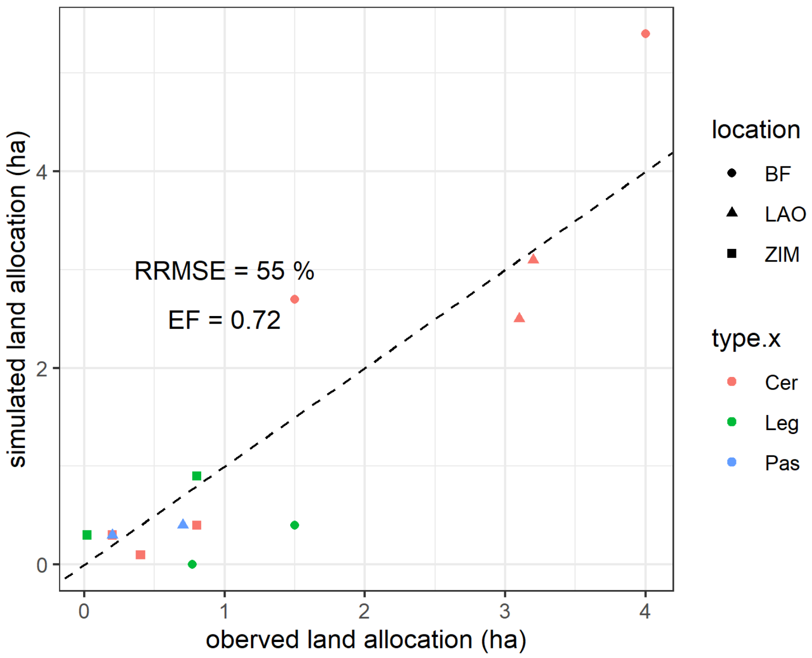

Figure 8: Observed and simulated land allocation for cereals (Cer), Legumes (Leg) and Pasture (Pas) at sites in Burkina Faso (BF), Lao-PDR (LAO) and Zimbabwe (Zim). RRMSE = Relative Root Lean Square Error, EF = model efficiency. Due to time constraints, all farms could not be modelled.

The farm model reproduced the variability in observed cropland allocation across the sites with model efficiency of 0.72 and relative RMSE of 55%. Legume area in Burkina was underestimated by the model (Figure 8). In Zimbabwe, legume area was overestimated, while cereal area was underestimated, leading to an overestimation of the share of legumes in the cropland.

3.4 Scenarios on subsidy across sites

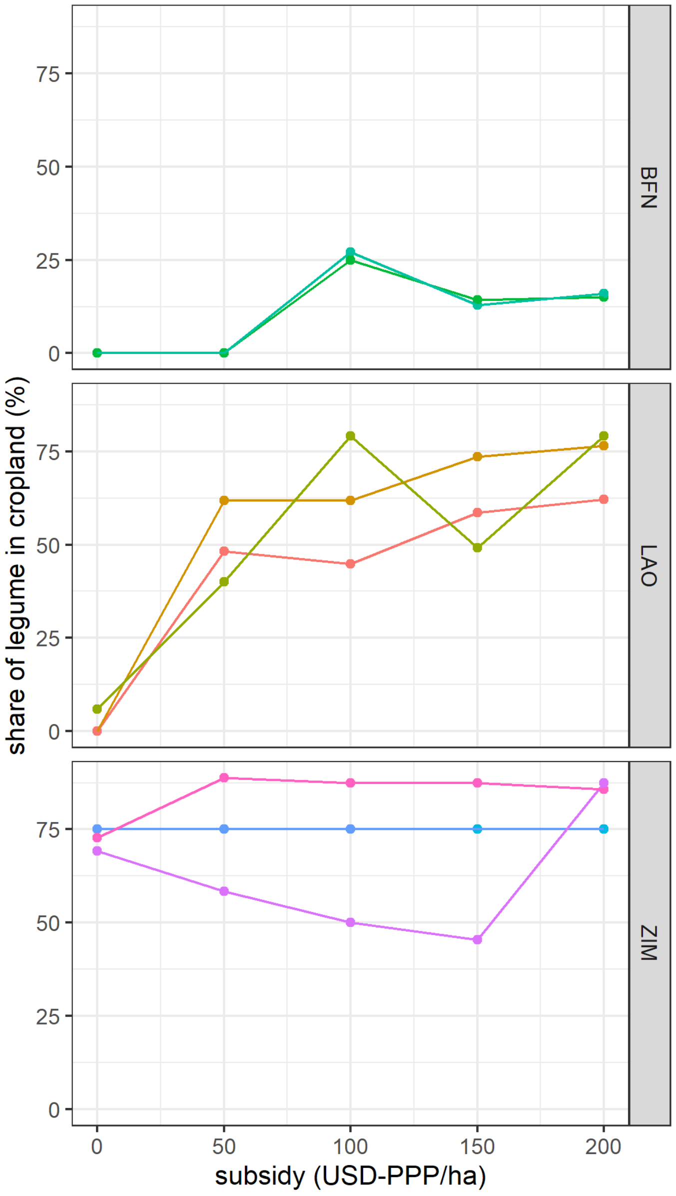

Figure 9: Impact of increasing subsidy for legume cultivation on legume integration into cropping systems at sites in Burkina (BFN), Lao PDR (LAO) and Zimbabwe (ZIM). Different colors correspond to contrasting farm types within a given site.

The impact of a subsidy for legume cultivation differed strongly across the sites (Figure 9). In LAO-PDR, a subsidy of 50 usd/ha was sufficient to drastically increase the share of legumes in the cropland, from 0 to around 50% for all farm types, replacing the maize cash crop with soybean cultivation. In Burkina, the same amount of subsidy was insufficient to trigger legume cultivation by farmers. Even greater amounts of subsidy up to 200 usd/ha only led to marginal increase in legume cultivation, with maximum of 15%. Possibly, cash availability was not the main constraint for farmers in Burkina Faso, and the competition for food crop (sorghum) could not be alleviated by the subsidy. In LAO-PDR, food self-sufficiency was achieved mainly on the lowland rice fields, so that integration of legume on the upland competed less with food production – and increase in the profitability of legume led immediately to more cultivation on the upland.

In Zimbabwe, the subsidy was somehow ineffective in trigger the integration of legumes, possibly because the share of legume in the baseline (=no subsidy) was already large. This large share of legume in the cropland was due to an overestimation of the model. The profitability of legume cultivation in Zimbabwe, in the baseline without subsidy, was surely mis-represented and further investigations are required. Possibly, the transaction cost for maize should be increased to reflect the propensity of farmers to produce their own maize rather than buying it on the market, even if the price is good. The transaction cost for groundnut should be increased to represent issues with market access for that crop.

Farmers would participate and grow more legume at different level of payment in LAO PDR, indicating that tailoring the payment program to the specificities of farm type would help increase its efficiency. On the contrary, in Burkina, different farm type required the same level of payment to cultivate more legume – indicating that a ‘one-size-fits-all’ approach could be sufficient. Overall, between-site variations were greater than within-site variations, indicating the smaller influence of farm type over site characteristics (technical coefficients for farm activities, transaction costs). More sites (Senegal and south Burkina, not simulated because of time constraints) should be added to the analysis to confirm this finding.

4 Future improvement of the model

We recognize that multiple objective optimisation might provide a richer way to represent farmers decision-making, but we believe that optimizing only income was of great value for the purpose of our study. The future improvement of the model will involve a sensitivity analysis to minimize the discrepancy between observed and simulated land allocation and herd sizes for typical farms in the study sites. In the current model, certain parameters lack literature values or survey data. These parameters can be adjusted through sensitivity analysis. The parameters include:

- **Transaction Costs on Input/Output Prices:** These costs, should be specific to each site to represent the additional effort required to bring external inputs to the farm. They are calculated as the ratio of the purchase price (e.g., for crops or labor) to the sale price at the farm gate.
- **Initial Grain Stocks and Cash:** Currently estimated based on the requirements for the first two simulation periods, but some farms were simulated “infeasible” due to very the food self-sufficiency constraint.
- **Maximum Off-Farm Time Allocation:** The maximum percentage of time a household member can dedicate to off-farm activities. They are based on survey data for Laos and Burkina, and

- **Hired Labor Market Capacity:** The maximum number of people available per day for hired labor.
- **Livestock Unit Prices (Burkina Faso):** Prices for livestock units sold were not estimated in Burkina Faso, Senegal data were taken.
- **Grazing Limitations and Crop-Livestock Integration:** In Burkina Faso, Senegal, and Zimbabwe, livestock grazing was not limited to crop residues availability. A maximum communal land area per farm should be calibrated through trial and error under baseline scenarios.
- **Minimum Household Daily Expenses:** The income calculation currently excludes minimum daily expenses. This parameter should align with the $1.90 PPP per day poverty line (source: World Bank) and country-specific PPP conversion factors (TrendEconomy).
- **Labor Requirements and yields of for Cropping Systems:** Sensitivity analysis should evaluate a ±30% variation in labor requirements/yields for different cropping systems.

These adjustments will ensure that the model better reflects the realities of farm management in the study sites, before simulating scenarios with subsidy on legume crops. The sensitivity analysis on technical coefficients and transactions costs would also help to understand what are the critical factors (e.g. productivity of the legume, economic attractivity of the cereal, proximity to markets) that drive the difference of results between sites.

The farms in southern Burkina Faso and Senegal were not included in the simulations at the time of this reporting. These farms will be added to the model in January 2025.

5 Perspectives/discussion

5.1 Reflection on payment for ecosystem services

The payments to trigger adoption of legume cultivation by farmers found in our study is in the range of typical payments for ecosystem services, e.g., around 100 usd/ha for forest regeneration in Brazil (Lemos et al., 2023), or 220 US$/ha/year to 580 US$/ha/year for farmers to replace intensive agriculture with agroforestry systems that preserve water quality in Brazil (Pissarra et al., 2021).

To the best of our knowledge, there are no current existing PES programs that deal with legume integration in particular. One common issue with PES programs is to define accurate (and cost-effective) metrics to assess the provision of ecosystem services (Salzman et al., 2018). The share of legumes in the cropland should be a good proxy for the provision of a ‘bundle’ of ecosystem services (provisioning and regulating services, as indicated in the introduction). Yet this connection between legume area and this bundle of ecosystem services needs to accurately quantified, in order to guaranty the cost-effectiveness of a program targeted at legumes (Benjamin and Sauer, 2018). The extent to which legumes help reduce the amount of fertiliser that is required for sustainable agricultural production, and the avoided carbon emissions, needs to be quantified (e.g., Cai et al.,2018). For this, experimental data on nitrogen fixation and nitrogen carry-over effects in crop rotation needs to be mobilised. Whether literature data is sufficient, or more data very specific to the site where the program is implemented is required – is an important issue to solve. How legumes contribute to decrease farmers reliance to pesticides also needs to be quantified (e.g., Yan et al., 2024), as this will critically influence the cost-effectiveness of the program.

PES transactions weigh 42 billons annually, and these are mainly programs financed by governments (Salzman et al., 2018). The increasing commitment of developed countries to transfer finance for e.g. climate change adaptation and mitigation (https://unfccc.int/news/cop29-un-climate-conference-agrees-to-triple-finance-to-developing-countries-protecting-lives-and) will surely offers new opportunities to develop and fund PES programs that could include legume cultivation.

5.2 Connection with science program Multifunctonal ladscape

Our study quantifies the level of incentives needed to compensate farmers in investing more land under legume which will lead to environmental positive outcome in the long term. By doing so, our study falls entirely in the scope of the research question "*Which incentive mechanism and solution clusters are most effective in delivering environmental outcomes across multiple ecosystem services"* of the Area of Work 1 (Solutions and Innovations: agroecology, nature-positive, regenerative, and nutrition-sensitive) of the science program Multifunctional landscape. This area of work will be an opportunity for the team, along with local partners to pursue this research question on tradeoff between economic short term needed by farmers, and long-term benefits of alternative agroecological practices. If we did not include any social, politic, macroeconomic scientist in this first stage of "proof of concept", it will be a priority in the next phase of development of this modeling approach to understand what are the key barriers in implementing the levels of incentives deemed efficient by our model. This reflection will completely be in line with the research question "*What are key subnational incentives and political economy barriers that influence policymaking and implementation related to MFLs, agroecology, and nature-positive outcomes*", of the Area of Word 4 (Institutions and policies).

In this proof of concepts, a significant amount of time was dedicated to merge the 6 datasets and create data that were comparable in terms of units (time, space, quantities, etc.). This result highlights the need to homogenize method and tools to assess performances, and our study shed light on the need to normalize measures and compare them, even if first data are of course field data under local units. This is in line with the research question of the AoW6 (Performance assessment and evidence generation): "*What frameworks, methods, and tools are available to assess interventions' performance and cascading effects in different dimensions across farm to landscape?".*

Mobilizing heterogenous data (labor, crop productivity, economic) from several case studies, we assessed the potential of subsidies to release short term constraints of farmers and increase land under legume that will entail benefits in the long term. Our study succeeded to “proof the concept” of an ad hoc modelling approach of ex ante assessment of incentivize agroecological transition. This exploration needs to be pursued in the next phase of the Initiative, i.e., the multifunctional landscape science program, where it could be a structuring cross-cutting theme between AoW 1, 4 and 6.

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7 Appendix

Appendix 1: determination of labor requirement per cropping system in Burkina Faso and Zimbabwe

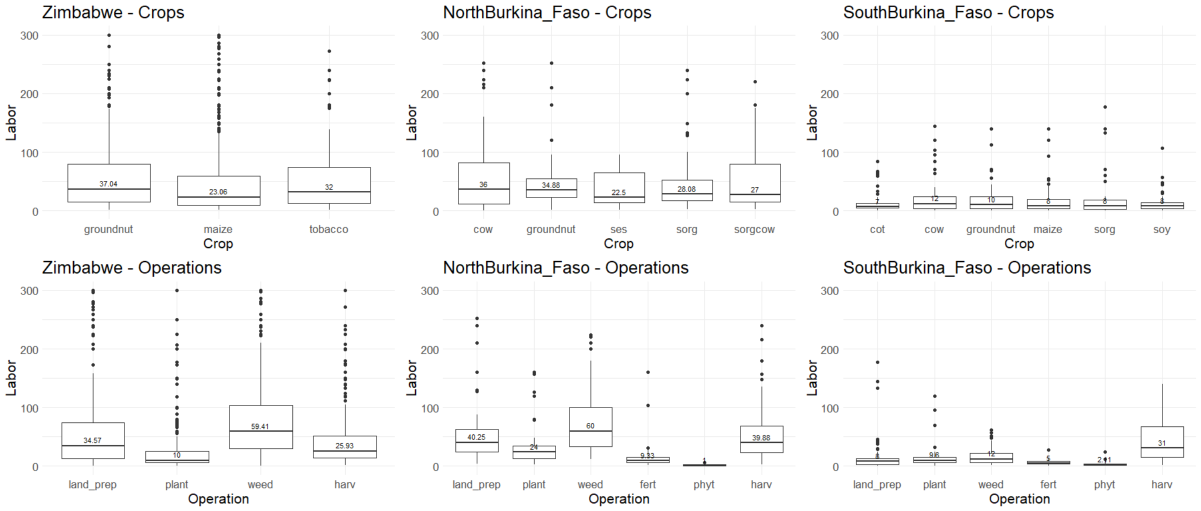

Figure 1: Boxplot of labor time by crops and operations across countries (Zimbabwe, North and South Burkina Faso)

An Analysis of variance (ANOVA) was performed, with logarithmic transformations applied to reduce variability and improve the normality of residuals. For single-factor ANOVA, the aim was to determine whether labor requirement for a specific operation differed across crops. When significant differences were found between crops, Tukey's post-hoc tests were conducted to identify specific crops exhibiting differences within the given operation. If no significant differences were found, the adjusted mean was used as the labor time for all crops. For two-factor ANOVAs, the analysis focused on the combined effects of crops and operations on labor times. In Zimbabwe, the results revealed significant differences in labor times across crops, operations, and their interaction, highlighting a combined influence of these two factors (fig. 2). Conversely, in Burkina Faso (North and South), no significant differences were observed for crops or the interaction between factors. Significant differences were only associated with the type of operations performed (fig. 3).

Figure 2: Boxplots of labor of all crops by operation in Zimbabwe

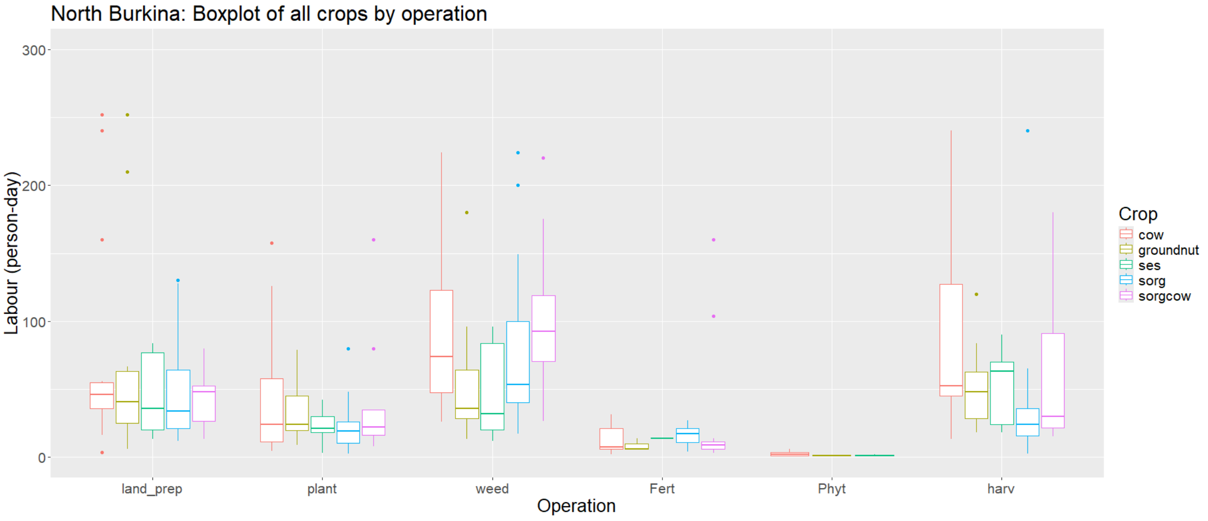

Figure 3: Boxplot of labor of all crops by operations in North Burkina Faso

The tables below summarize the labor time values obtained from the ANOVA analyses for each cropping system by period and country. They also include a description of each period by country. It should be noted that labor times for Period 5 (dry season) are considered null due to the absence of agricultural activities during this period.

Table 1: Description of working periods and labor times by country (data: Burkina Faso, Zimbabwe)

Period					
Zones	Period 1	Period 2	Period 3	Period 4	Period 5
North Burkina Faso	Land preparation, sesame, cereal and legume sowing	Weeding and legume phytosanitary	Legume and sesame harvest	Cereal harvest	Dry season
South Burkina Faso	Land preparation, cotton cereal and legume sowing	First weeding and phytosanitary	Second weeding and phytosanitary	Cotton, cereal and legume harvest	Dry season
Zimbabwe	Land preparation	Sowing	Weeding	Legume and cereal harvest	Dry season diversification activities
North Burkina Faso					
Cropping sytem	Crop	Period 1	Period 2	Period 3	Period 4
Sesame-Low Intensification	Sesame	94,55488	102,2927	44,70118	
Cereal-Rain-Low Intensification	Sorghum	94,55488	102,2927		22,64473
Cereal-Legume-Rain- Low Intensification	SorghumCowpea	94,55488	102,2927	22,35059	22,35059
Legume- Low Intensification	Cowpea	94,55488	102,2927	68,03389	
Legume- Low Intensification	Groundnut	94,55488	102,2927	44,70118	
Legume-Medium Intensification	Cowpea	94,55488	118,087674	68,03389	
CV (%)		0	6,145588857	38,67954341	0,9244889
South Burkina Faso					
Cropping System	Crop	Period 1	Period 2	Period 3	Period 4
Cotton-Intensification	Cotton	29,71709	25,093719	17,71884	54,63497
Cereal-Rain-Intensification	Maize	29,71709	25,915941	21,385507	54,63497
Cereal-Rain- Low Intensification	Maize	29,71709	25,21356	16,71884	54,63497
Legume- Low Intensification	Groundnut	29,71709	15,14667	16,71884	54,63497
Legume- Low Intensification	Soya	29,71709	15,14667	16,71884	54,63497
Legume- Medium Intensification	Groundnut	29,71709	18,216114	16,71884	54,63497
Legume- Medium Intensification	Soya	29,71709	17,14667	16,71884	54,63497
Legume- Medium Intensification	Cowpea	29,71709	24,39667	16,71884	54,63497
Cereale-Low Intensification	Sorghum	29,71709	17,99667	18,51884	54,63497
CV (%)		0	22,373243	8,9702134	0
Zimbabwe					
Cropping System	Crop	Period 1	Period 2	Period 3	Period 4
Tobacco-Intensification	tobacco	99,07876	15,40224	89,07944	59,28482
Cereal-Rain-Intensification	maize	80,69281	26,19544	105,2917	44,22756
Cereal-Rain- Low Intensification	maize	65,4352	9,07922	112,0469	21,41242
Legume- Low Intensification	groundnut	65,4352	22,95397	112,0469	46,47795
CV(%)		20.5871014	41.77154004	10.35816761	36,76900094