Multicriteria assessment of alternative cropping systems at farm level. A case with maize on family farms of South East Asia

Juliette Lairez, Damien Jourdain, Santiago Lopez-Ridaura, Chanthaly Syfongxay, François Affholder

To cite this version:

Juliette Lairez, Damien Jourdain, Santiago Lopez-Ridaura, Chanthaly Syfongxay, François Affholder. Multicriteria assessment of alternative cropping systems at farm level. A case with maize on family farms of South East Asia. Agricultural Systems, 2023, 212, pp.103777. ⟨10.1016/j.agsy.2023.103777⟩. ⟨hal-04385611⟩

HAL Id: hal-04385611

https://hal.inrae.fr/hal-04385611v1

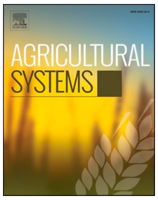
Submitted on 10 Jan 2024

Agricultural Systems 212 (2023) 103777

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy



Multicriteria assessment of alternative cropping systems at farm level. A case with maize on family farms of South East Asia

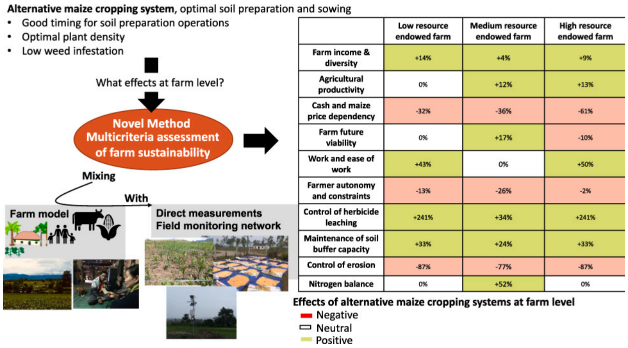
Juliette Lairez[a,b,*], Damien Jourdain[c,d,e], Santiago Lopez-Ridaura[f], Chanthaly Syfongxay[g], François Affholder[a,b,h]

[a] CIRAD, UPR AIDA, F-34398 Montpellier, France
[b] AIDA, Univ Montpellier, CIRAD, Montpellier, France
[c] CIRAD, UMR G-EAU, Hatfield 0028, South Africa
[d] G-EAU, Univ Montpellier, AgroParisTech, CIRAD, IRD, IRSTEA, Montpellier SupAgro, Montpellier, France
[e] Centre for Environmental Economics and Policy in Africa (CEEPA), University of Pretoria, Hatfield 0028, South Africa
[f] CGIAR initiative on Sustainable Intensification of Mixed Farming Systems (SI-MFS), Sustainable Agrifood Systems Program (SAS), International Center for Maize and Wheat Improvement (CIMMYT), Texcoco, Mexico
[g] Provincial Agriculture and Forestry Office (PAFO), Phonesavanh, Laos
[h] Universidade Eduardo Mondlane, Faculdade de Agronomia e Engenharia Florestal, Maputo, Mozambique

HIGHLIGHTS

- We applied a novel method to explore effects of changes in cropping systems on farm sustainability.
- Farm modelling was combined with direct measurement to jointly feed a multicriteria assessment of maize-based farms.
- The farm model provided insights on the feasibility of changes in cropping systems.
- Optimal soil preparation and sowing for maize fields appeared key to improve farms' sustainability in a study case in Laos.
- In Laos, moderate changes in crop management would improve farm income while reducing herbicide leaching risks.

GRAPHICAL ABSTRACT



	Low resource endowed farm	Medium resource endowed farm	High resource endowed farm
Farm income & diversity	+14%	+4%	+9%
Agricultural productivity	0%	+12%	+13%
Cash and maize price dependency	-32%	-36%	-61%
Farm future viability	0%	+17%	-10%
Work and ease of work	+43%	0%	+50%
Farmer autonomy and constraints	-13%	-26%	-2%
Control of herbicide leaching	+241%	+34%	+241%
Maintenance of soil buffer capacity	+33%	+24%	+33%
Control of erosion	-87%	-77%	-87%
Nitrogen balance	0%	+52%	0%

Effects of alternative maize cropping systems at farm level
🟥 Negative
☐ Neutral
🟨 Positive

ARTICLE INFO

Editor: Jagadish Timsina

Keywords:
Bio-economic farm model
Indicators
Smallholder farms
Laos

ABSTRACT

CONTEXT: Integration of farms into markets with adoption of maize as a cash crop can significantly increase income of farms of the developing world. However, in some cases, the income generated may still be very low and maize production may also have strong negative environmental and social impacts.
OBJECTIVE: Maize production in northern Laos is taken as a case to study how far can farms' performance be improved with improved crop management of maize with the following changes at field level: good timing and optimal soil preparation and sowing, allowing optimal crop establishment and low weed infestation.

---

* Corresponding author at: CIRAD, UPR AIDA, F-34398 Montpellier, France.
E-mail address: juliette.lairez@cirad.fr (J. Lairez).

https://doi.org/10.1016/j.agsy.2023.103777
Received 9 March 2023; Received in revised form 7 September 2023; Accepted 26 September 2023
Available online 7 October 2023

Cash crop cultivation
Multidimensional farm sustainability

METHODS: We compared different farm types' performance on locally relevant criteria and indicators embodying the three pillars of sustainability (environmental, economic and social). An integrated assessment approach was combined with direct measurement of indicators in farmers' fields to assess eleven criteria of local farm sustainability. A bio-economic farm model was used for scenario assessment in which changes in crop management and the economic environment of farms were compared to present situation. The farm model was based on mathematical programming maximizing income under constraints related to i) household composition, initial cash and rice stocks and land type, and ii) seasonal balances of cash, labour and food. The crop management scenarios were built based on a diagnosis of the causes of variations in the agronomic and environmental performances of cropping systems, carried out in farmers' fields.

RESULTS AND CONCLUSIONS: Our study showed that moderate changes in crop management on maize would improve substantially farm performance on 4 to 6 criteria out of the 11 assessed, depending on farm types. The improved crop management of maize had a high economic attractiveness for every farm type simulated (low, medium and high resource endowed farms) even at simulated production costs more than doubling current costs of farmers' practices. However, while an improvement of the systems performance was attained in terms of agricultural productivity, income generation, work and ease of work, herbicide leaching, improved soil quality and nitrogen balance, trade-offs were identified with other indicators such as erosion control and cash outflow needed at the beginning of the cropping season.

SIGNIFICANCE: Using farm modelling for multicriteria assessment of current and improved maize cropping systems for contrasted farm types helped capture main opportunities and constraints on local farm sustainability, and assess the trade-offs that new options at field level may generate at farm level.

1. Introduction

The very low farm incomes and yields that prevail under rainfed subsistence farming in South-East Asia (SEA), as in most regions of the 'Global South', call for a profound transformation of farming systems to achieve the UN sustainable development goals of "zero hunger" and "no poverty". Market integration and increase of agricultural productivity are often considered key to a way out of this poverty trap of subsistence farming (Akram-Lodhi, 2008; Alexander et al., 2010; Pretty et al., 2011; The Montpellier Panel, 2013). In the past three decades, some regions in SEA witnessed a rapid integration of subsistence farming systems into markets with adoption of maize monocropping, in response to increase in maize demand for the thriving livestock feed industry (Keil et al., 2008; Luckmann et al., 2015). As a consequence, farmers increased their agricultural production per unit of land area and labour by adopting technologies such as fertilizers, herbicides, improved hybrid seeds, and mechanization. This market integration led to an improvement of the farmers' wealth compared to the former subsistence system based on rainfed rice shifting cultivation in addition to lowland paddy rice (Kallio et al., 2019). In most cases, however, the resulting income is still low and maize cropping systems have strong negative environmental and social impacts (Kyeyune and Turner, 2016; Shattuck, 2021).

Laos is a good example of this SEA dynamics on maize cultivation. Subsistence rice-based shifting cultivation started to decline 20 years ago, replaced by market-based production of maize (Vongvisouk et al., 2014). Maize production increased tenfold between 2002 and 2012 due to both an expansion of cultivated areas (multiplied by 4 over the same period) and an increase in maize yields (Cramb et al., 2016). Maize is mainly cultivated in the mountainous North of the country. In a study case of a plain surrounded by mountains, detailed studies at cropping system level (Lairez et al., 2020; Lairez et al., 2023) have clearly shown that the current management of maize is not sustainable. Economic profitability is declining due to weed infestation leading to higher production costs, increase use of herbicides, or declining yields (Lairez et al., 2020). It was shown that these issues are mostly the result of the following sequence of effects. Due to poorly effective sowing equipment and insufficient access to soil tillage machinery, maize crops are not timely and successfully established. The long delay between tillage and sowing operation, the insufficiently crushed soil aggregates after tillage that hampers the proper operation of the sowing machine, and the frequent low stand density that often results from these shortcomings, all causes a strong weed pressure requiring ever more labour or herbicides to cope with weeds, and decreases the efficiency of use of fertilizers (Lairez et al., 2020).

The concept of sustainable intensification was forged in response to this typical failure of the so called "conventional intensification" of agriculture (Tilman et al., 2002). Sustainable intensification is defined as follows: "producing more output from the same area of land while reducing the negative environmental impacts and at the same time increasing contributions to natural capital and the flow of environmental services" (Pretty et al., 2011). In Lairez et al. (2023), an improved crop management of maize was hypothetically designed to correct the main flaws in the technical management (described above) and compared to the current management of maize using a number of indicators at field level. This previous study suggested a room of improvement in both the economic and environmental dimensions at field level, but the impact of improved crop management at farm level remained uncertain. In the present study, we hypothesize that room for progress on performance at farm level could be substantial through improvements in crop management within the current production systems.

Comparison of farm performance under current practice and candidate alternatives is needed to assess benefits and constraints that new options at field level may generate at farm level. Such multidimensional assessment can be done using a multi-attribute (also referred to as multicriteria) approach based on ex post or ex ante quantification of indicators aggregated into criteria (Vasileiadis et al., 2013; Iocola et al., 2020; Craheix et al., 2012; Alary et al., 2020) or using an ex ante "integrated approach" integrating farms' structural constraints, economic and biophysical processes into farm models (see the review of Janssen and van Ittersum, 2007 and examples of studies applying this integrated approach: Dogliotti et al., 2005; Timler et al., 2020; Ditzler et al., 2019).

In this study we applied a novel method combining both approaches, to assess how much the local sustainability of farms that have been conventionally intensified in the past decades can be improved thanks to changes in farmers' crop management practices that would be reachable under their current economic environment and given their constraints relative to cash, labour and land availability. To be claimed as "sustainable", agriculture must meet the needs of the present generation without compromising the needs of future generation (Brodt et al., 2011). However, sustainable agriculture is not unique or universal and has to be grounded into the local context (Pretty, 2008). By "local sustainability assessment", we mean comparing farms' performance on relevant local criteria embodying the three pillars of sustainability (environmental, economic and social) and identifying their relative strengths and weaknesses (López-Ridaura et al., 2002). This approach differs from systemic and generic multicriteria sustainability assessments which assess farm sustainability against a set of criteria meant to be universal (Brentrup et al., 2004) or targeting absolute benchmarks or "desirable levels of sustainability" (Meul et al., 2008; Hani et al., 2003; Hammond et al., 2021).

The objectives of the study are: i) to explore the advantages and limits of the new method proposed, ii) to compare the multidimensional performance of current maize-based farming systems, accounting for their diversity (resource endowment and livelihood strategy) in a region typical of the issues resulting from a recent conventional intensification of crops, iii) to assess ex ante the sustainability benefits, impacts and constraints brought by changes in farmers' crop management practices at farm level for different farm types.

2. Method

2.1. Site description

The study's location was Kham Basin in Xieng Khouang province of northern Laos (19°38′N, 103°33E). Kham basin is a large alluvial plain at 500 to 600 m of elevation a.s.l, surrounded with mountains reaching up to 1400 m of elevation. Mixed crop-livestock farming systems largely predominate in the landscape. Paddy rice is continuously cropped on the lower terraces along water courses which represents 31% of the arable land (Lestrelin, 2016). This paddy rice is cultivated for household consumption and the possible surplus is sold. The major part of the land in the plain is non-irrigated and above the level of watercourses, bearing rainfed crops with soil texture ranging from sandy to clay loam types (Lairez et al., 2023). In the middle of the 2000s, after the integration of the formerly subsistence-oriented farms into markets, this rainfed component of the cropping system switched from manually cultivated upland rice under shifting cultivation with extremely low yields, to continuous maize cash crop systems with the use of hybrid seeds, mechanization, herbicides, mineral fertilizers, and consistently higher yields (Lairez et al., 2020). Nowadays shifting cultivation is abandoned in Kham Basin and maize is cultivated every year on this non-irrigated land during the rainy season from May to November. The harvest is entirely sold to local markets or to traders from neighbouring Vietnam.

2.2. General approach

Our approach involved two steps: (i) Assessment of the economic attractiveness of an alternative maize cropping system (designed to reduce herbicide use and increase yields), using a farm model, and (ii) Multicriteria assessment of farms' performance under different scenarios, using the farm model to make simulations (with and without the alternative maize cropping system) and indicators assessed using both the outputs of the farm model and direct measurement made in a previous study (Lairez et al., 2023) (Fig. 1).

Alary et al. (2016) defined the "economic attractiveness" at farm scale of an innovative, supposedly more sustainable cropping system, as the expected increase of net household total income at farm level that would be achieved by adopting that cropping system, while satisfying farm constraints relative to cash, labour and land availability over time, and as compared to the current system.

In this context of highly constrained agriculture, we assumed that an alternative maize cropping system considered "economically attractive" was a necessary (but not sufficient) condition under which those alternatives could be considered as sustainable options for the different maize-based farms. In this study, our approach was as follows: if the alternative cropping system was considered "economically attractive" at farm level, its effects on other criteria of farm performance were assessed.

2.3. Farm model design

The farm model was designed to simulate the strategic decisions of farmers by optimizing farm activities under multiple constraints and toward a single farmer strategic objective of maximizing farm income (Fig. 2).

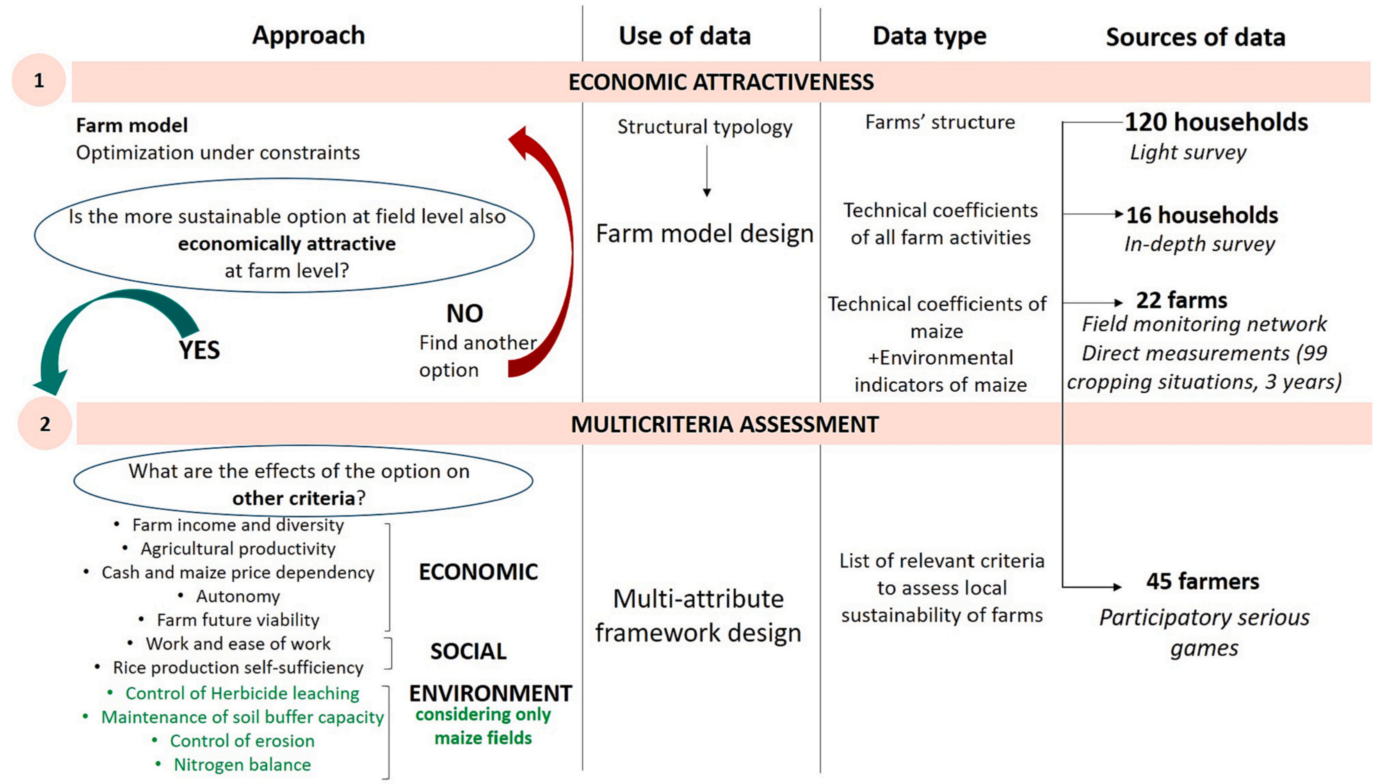


Fig. 1. The approach used to assess benefits and constraints that new options at field level may generate at farm level.

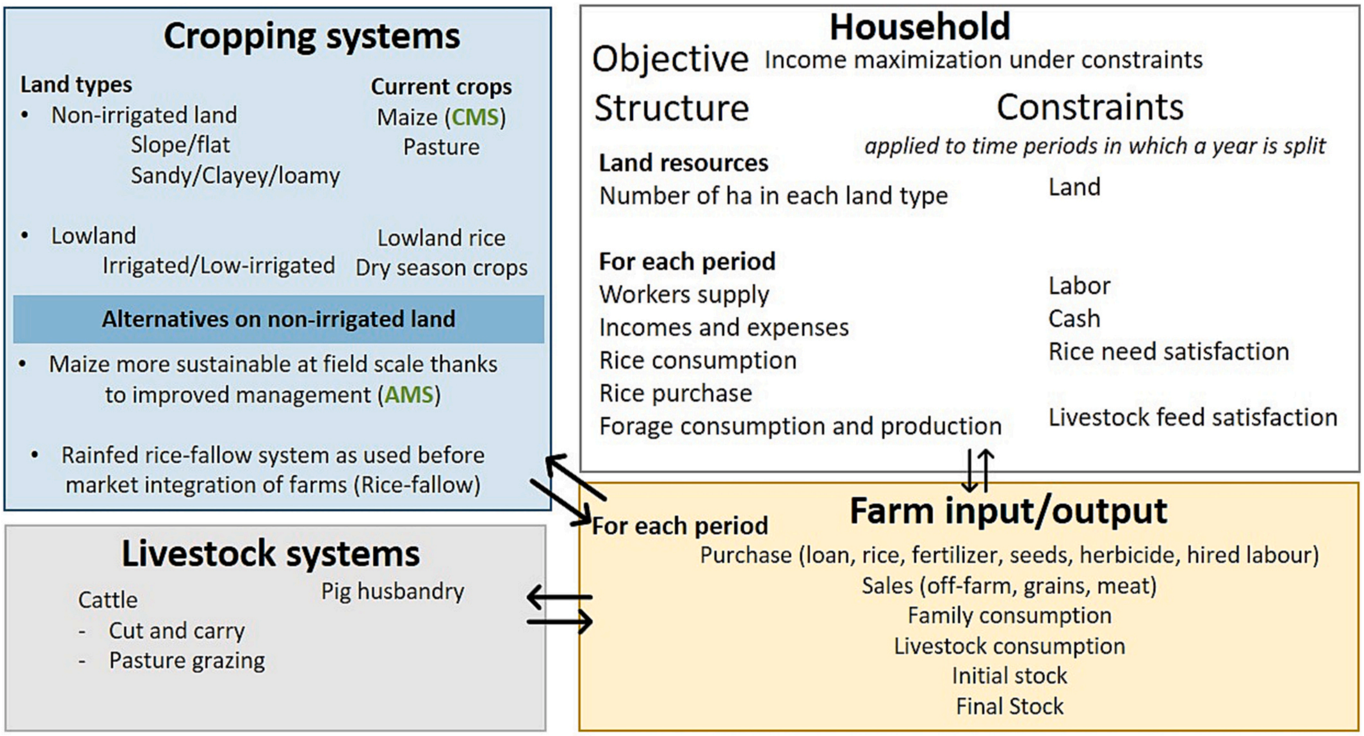


Fig. 2. Overview of the farm model (CMS = current management of maize; AMS = alternative management of maize).

The model represented different farm types and the key interactions between farm structure and its environment. These interactions were captured by building a structural typology of maize-based farms. The structural typology of farms was obtained using the data from 120 farm household surveys (see “Light survey”, Fig. 1) conducted in six villages of the Kham Basin (Dokham, Laeng, Lé, Houat, Xay and Nadou). The 120 households chosen for this light survey were selected from a census conducted in 2016 on all farmers of the six villages (Lestrelin and Kiewvongphachan, 2017). All the households selected were at the same level of market integration for maize, but differed in land size and land allocation. The data recorded on the 120 households included information about farm land allocation, family size and workforce, farm equipment (motorized equipment for agricultural activities and for transport), the farmers’ on and off-farm activities, and income generated for the period 2016–2017. We performed a principal component analysis (PCA) and a hierarchical cluster analysis to obtain relatively homogeneous types of farms.

We then conducted in-depth surveys and farm visits with a subsample of 16 farms (Fig. 1). The number of farms selected per farm type (2 to 8 farms per type) was proportional to the distribution of farm types in the 120-household sample. During these 4 to 5-h-long in-depth-surveys we collected detailed data on farm productions, on crop/livestock management, seasonality of work, input/output prices, seasonality of family expenses and treasury, soil types, surfaces, distances between fields, and cattle herd size.

The data collected in this in-depth survey was used to calculate the technical coefficients of crop and livestock activities (inputs and outputs) to be used in the farm model, except for maize technical coefficients that were derived from direct measurement made in a previous study (Lairez et al., 2023). In Lairez et al. (2023), a field monitoring network of 99 cropping situations (2016–2018) covered the diversity of maize crop management and soil characteristics of Kham Basin. From this analysis, five main types of “current maize cropping systems” (CMS) were obtained and considered in the farm model: (i) CMS-MotoPoorSoil: motorized sowing on poor sandy soils, (ii) CMS-ManPoorSoil: manual sowing on poor sandy clay loam soils, (iii) CMS-MotoNoHerbi: motorized sowing on clay loam soils and no herbicide use, (iv) CMS-Moto: motorized sowing on clay soils, and (v) CMS-ManFertileSoil: manual sowing on fertile clay loam soils. The technical coefficients of CMS are described in details in Lairez et al. (2023) and are summarized in Table 1.

Hypothetical alternative management versions of CMS, named hereafter “AMS” were designed using direct measurement in a diversity of farmers’ fields and assessed for their sustainability at field level in Lairez et al. (2023). Three AMS were considered in the farm model, all having an optimal soil preparation and sowing thanks to the use of a “best machinery” (not yet available to the farmers in the region) able to result in an optimal plant density and low weed infestation. The different AMS differed by nitrogen input use depending on soil type (Table 1). Compared to CMS, all AMS required higher production costs (less herbicide but more fertilizer), had a delayed sowing by one month and a total labour requirement equal or below (if the corresponding CMS was hand sown) that of CMS. In our model, extra costs of AMS were accounted for, excepted the costs to acquire or rent the best machinery for soil preparation and sowing. Such costs were unknown and kept the same as motorized CMS. However, a sensitivity analysis of the cultivation costs was done (see SCEN2-i, section 2.4) to conclude about the economic attractiveness of AMS.

The cropping system of shifting cultivation rice-fallow (hereafter named rice-fallow system) that prevailed on rainfed land before the market integration of farms was also considered in the farm model, in order to identify the maize price level below which simulated farms replaced CMS or AMS by rice-fallow system (see SCEN3 in section 2.4). Nowadays the rice-fallow system is not cultivated anymore in Kham Basin, its technical coefficients were taken from Lienhard et al. (2004) regardless the soil type, considering a 5-years fallow period (managed by slash-and-burn before sowing) between two crop cycles on the same field.

The model was built using GAMS software (version 22.5). The single goal of maximizing one-year farm income was considered in the model. However, beside income maximization we considered a number of constraints applied to five time periods in which a year was split: land,

Table 1

Maize cropping systems description and parameters ('technical coefficients') used in the farm model depending on simulation scenarios. Data for baseline scenario in columns with a blank background, data for other scenarios (SCEN) in columns with grey background.

Soil type	Sandy and sandy clay loam			Clay and clay loam			Fertile clay loam	
Maize cropping systems	*CMS-MotoPoorSoil*	*CMS-Man PoorSoil*	AMS-sandy	*CMS-Moto Noherbi*	*CMS-Moto*	AMS-clay	*CMS-ManFertileSoil*	AMS-FertileClayLoam
Selling Yield (ton/ha)	2.9	2.2	5.9	2.9	3.8	5.8	3.8	5.8
Labour requirement (man-day/ha)	51	72.75	51	51	51	51	72.75	51
Cost (USD/ha)	187	186	SCEN1: 415 SCEN2–1: 465	243	265	SCEN1: 410 SCEN2–1: 460	169	SCEN1: 293 SCEN2–1: 343
Gross margin (USD/ha)	310	190	SCEN1: 594 SCEN2–1: 544	253	385	Scen1: 582 SCEN2–1: 532	481	SCEN1: 699 SCEN2–1: 649
Labour productivity (USD/man-day/ha)	6	2.6	SCEN1: 11.6 SCEN2–1: 10.7	5	7.5	SCEN1: 11.4 SCEN2–1: 10.4	6.6	SCEN1: 13.7 SCEN2–1: 12.7

CMS stands for 'Current Management of Maize cropping Systems', with CMS-MotoPoorSoil: motorized sowing on poor sandy soils, CMS-ManPoorSoil: manual sowing on poor sandy clay loam soils, CMS-MotoNoHerbi: motorized sowing on clay loam soils and no herbicide use, CMS-Moto: motorized sowing on clay soils, CMS-ManFertileSoil: manual sowing on fertile clay loam soils. Herbicide use is above recommended doses for all CMS except CMS-MotoNoHerbi. AMS stands for 'Alternative Management of maize cropping Systems' and are hypothetical alternative cropping systems with well mastered crop establishment ensuring reduction in both yield gap and herbicide use (down to recommended dose) on different soil types. SCEN1: production costs of AMS as calculated in Lairez et al. (2023), SCEN2–1: additional production cost of 50 USD for AMS compared to SCEN1. Only the parameters of the first scenario of SCEN2-i are provided for cost, gross margin and labour productivity, the others SCEN2-i corresponding to an increment of i*50 USD in the production cost of AMS at the beginning of the cropping season.

labour, cash, rice needs, and livestock feed (see supplementary material, appendix A). The model was designed to consider distinct simulations for each of the 16 farms surveyed in the in-depth survey. 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 rice stock available for consumption at the beginning of the year. Further details about the farm model, its full set of equations and calibration procedure can be found in Supplementary material, appendix A.

The model quality was assessed using an analysis of the consistency between simulated and observed farm plan on the 16 farms, following the approach used by Affholder et al. (2010) as derived from Norton and Hazell (1986). We used two indicators on cultivated areas: mean absolute deviation (MAD) which quantifies the absolute deviations of predictions, and model efficiency (see Supplementary material, appendix A).

2.4. *Economic attractiveness assessment*

The economic attractiveness of maize cropping systems was assessed using four different simulation scenarios: Baseline, SCEN1, SCEN2-i and SCEN3. All simulation scenarios were made on a full calendar year, farm constraints and objective remaining unchanged in the model across all scenarios:

(i) The baseline scenario represented the simulation of current cropping and livestock systems.

- Simulations with Alternative maize systems (AMS) included in the list of cropping system options available to simulated farms:

(ii) The scenario SCEN1 considered the following production costs of AMS: fertilizer, seeds, herbicide reduced to recommended doses, and current cost of soil preparation and sowing.
(iii) The scenario SCEN2-i was a sensitivity analysis of the economic attractiveness of AMS to the production costs. A gradual incrementation (i*50 USD) of production costs of AMS was done, applied to the beginning of the cropping season, until AMS were no longer simulated as economically attractive. SCEN2-i was used to determine the maximum affordable cost of the optimal soil preparation and sowing for AMS in the different farm types.

We defined the economic attractiveness of AMS for a farm in a given scenario as the simulated conversion rate of land from CMS to AMS (adapted from Alary et al., 2016) from the baseline scenario to the given scenario. In addition, for a given farm simulated in SCEN1 and SCEN2-i, if this conversion rate was above or equal to 50%, AMS was considered "economically attractive".

- Simulations with Rice-fallow system included in the list of cropping system options available to simulated farms and decrease of maize selling price until maize abandonment:

(iv) The SCEN3-CMS scenario was used to assess the sensitivity of the relative areas of pasture, rice-fallow system and maize to decrease in maize selling price, when maize option available to the farm model was only CMS.
(v) The SCEN3-AMS scenario was used to assess the sensitivity of the relative areas of pasture, rice-fallow system and maize to decrease in maize selling price, when maize options available to the farm model were AMS and CMS.

The scenarios SCEN3-CMS and SCEN3-AMS were designed to identify the maize price level below which simulated farms abandon CMS or AMS, respectively, and replaced it with pasture or rice-fallow system. The farm income simulated after abandonment of maize was calculated and compared to the farm income obtained in the baseline and SCEN1 scenarios respectively.

2.5. *Multicriteria assessment of farms' performance*

To compare farms' multiple performance when simulated with and without AMS, a multi-attribute framework was built following the 3 pillars of sustainability approach (economic, social and environnement). The pillars were divided in 11 local sustainability criteria and assessed using 25 indicators. The 11 criteria were identified in a previous study at farm and field levels, specifically for the study region (Lairez et al., 2020), combining a cropping system analysis and participatory serious games with 45 farmers (Fig. 1). The criteria assessed were as follows: farm income and diversity (in income sources), agricultural productivity, cash and maize price dependency, farm future viability, rice production self-sufficiency, work and ease of work, farmer autonomy and constraints, control of herbicide leaching, maintenance of soil buffer capacity, control of erosion, and nitrogen balance.

The indicators used to assess the criteria were selected by the authors. Different sources of data were used to quantify the indicators (Table 2). The farm model was used to assess most of the indicators, but environmental indicators were assessed only for maize fields, using the direct measurement made in a previous study at field level (Lairez et al., 2023). Further details on the calculation of the indicators can be found in Supplementary Material, Appendix B (Table S2).

From this study, it was not possible to state whether any of the farm scenarios were sustainable per se, but rather we compared the various scenarios to identify which scenarios (and for which farm types) were more sustainable compared to others. To simplify the graphical representation of farms' performances on criteria, the indicators were first normalized using the procedure of "Min-Max normalization" after Pollesch and Dale (2016) detailed in supplementary material (Appendix C) and resulting in dimensionless values ranging from 0 (lowest contribution to sustainability) to 1 (highest contribution to sustainability). This procedure normalized each indicator according to its distribution on the 16 farms modelled in the baseline and the SCEN1.

Then, the indicators were aggregated to the criteria level on a 100 grades scale using a geometric mean also detailed in supplementary material. The geometric mean was chosen instead of arithmetic mean to avoid low indicator scores to be compensated by high scores on other indicators composing a criterion (Lairez et al., 2016; Pollesch and Dale, 2016).

3. Results

3.1. Typology and farm selection for farm modelling

The principal component analysis (PCA) and hierarchical clustering resulted in three farm types, displayed in Table 3. "Type 1 – Low resource endowment (LRE)" represented maize farms with the lowest level of resource endowment (cattle, asset, cultivated area), 18% of them were rice constrained (8% of the 120 farms) without access to irrigated paddy field and bought rice on local market for family consumption, using the income generated from off-farm activities or maize selling. Compared to the two other farm types, Type 1-LRE had the smallest cultivated area (2.6 ha). 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 and the income they obtained from maize selling was used for children education, healthcare, housing and investing in farming activities. 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. The fully detailed results on PCA and hierarchical clustering are given in Supplementary Material (Appendix D).

3.2. Farm model quality

Calibration allowed to reach satisfactory values of 0.63 for model efficiency and of 0.28 ha for MAD (Table S.5 in Appendix E). The model represented accurately land allocation for maize and for lowland rice but overestimated slightly the land allocation of dry season crops (see the bars "Obs" and "Baseline" in Fig. 3, further details can be found Table S.6 in Supplementary Material). The simulated number of cattle units was above the corresponding observed values for farm Type 1-LRE (Table S.6 Supplementary Material). Under the baseline scenario, two farms were simulated with motorized maize sowing instead of hand sowing (Fig. 3).

3.3. Assessment of the economic attractiveness of AMS

In 81% of the simulated farms, alternative management of maize cropping system (AMS) was economically attractive even at an additional cost of 100 USD ha^{-1} on top of the production cost used for AMS

Table 2

Criteria and indicators used to assess local farm sustainability, units in brackets. See Supplementary Material for further details on indicators' calculation.

	Source of data for indicators' computation
ECONOMY - Farm income & diversity	
Total farm income (USD/year): Gross value from livestock and crop total sales plus income generated from off-farm activities minus the sum of all expenses for crop, livestock, hired labour, buying food (rice), fixed costs and loan interests	Farm model
Per capita Farm income (USD/capita/ day): Total daily farm income per household Member	Farm model
Income diversity score (score): Score accounting for diversity in income sources (score)	Farm model
Cash inflow regularity (score): Score accounting for regularity in cash inflow, number of periods of the year during which income is generated	Farm model
ECONOMY- Agricultural Productivity	
Product from farm activities (USD/ha): Product from livestock and crop total sales plus the value of rice produced and consumed per hectare of land cultivated	Farm model
Labour productivity from farming activities (USD/person-day): (Total farm income + gross margin of rice produced and consumed -income generated from off-farm activities)/ total labour used by farm activities. If off- farm income>total farm income + gross margin of rice produced and consumed, this indicator was scored to 0.	Farm model
ECONOMY- Cash and maize price dependency	
Income dependency on maize price fluctuation (%): Estimated by decreasing by 20% maize selling price and by calculating, with a fixed farm plan, the ratio: ([product from maize selling with current price]-[product from maize selling with price decreased])/total farm income	Farm model
Cash outflow needed at the beginning of the cropping season (USD): Total expenses needed in first period simulated for crop, livestock, hired labour, rice bought and fixed costs.	Farm model
ECONOMY - Farm future viability	
Farm equipment/heir (equipment/heir): sum of farm equipment per heir (average number of descendants per family using the sample of 16 farms). Farm equipment are the following: seed drill, milling machine, threshing machine, shelling machine, rototiller, truck, motorbikes, and cars.	Light survey + Farm model
Cattle unit/heir (cattle unit/heir): Total cattle owned by the household per heir	Farm model
Land/heir (ha/heir): Total land cultivated per heir	
Number of affordable additional dependants: Number of additional dependant that the farm could feed and pay for education provided the farm does not fall below the $1.9/day poverty line.	Farm model
ECONOMY- Farmer autonomy and constraints	
Selling constraints at maize harvest (USD): Cash available before harvest minus the expenses after harvest	Farm model
Lowland constraint to higher income (USD/ha of lowland): Marginal increase of income per additional unit (hectare) of lowland area, calculated by GAMS software	Farm model
Non-irrigated land constraint to higher income (USD/ha): Marginal increase of income per additional unit (hectare) of non-irrigated area	Farm model
Labour constraint to higher income (USD/day): Marginal increase of income per additional labour unit (person.day) available during labour peak periods	Farm model
Indebtedness rate (%): Loan (USD)/total farm income (USD)	Farm model
SOCIAL - Rice production self-sufficiency	
Rice production self-sufficiency (score): If Rice produced - total rice needs for household consumption>0, indicator score = 100. If Rice produced - total rice needs for household consumption<0, this indicator is calculated with	Farm model

(*continued on next page*)

Table 2 (*continued*)

	Source of data for indicators' computation
the ratio Rice produced/total rice needs for household consumption	
SOCIAL- Work and ease of work	
Workload (%): Total work required for farm and off-farm activities over total labour force available	Farm model
Frequency of workload peak (%): period during a year with peak, a peak is reached when workload in a period is>70%	Farm model
Ease of work maize (score 10–100): Score aggregating 2 variables: Tool used for sowing (hand/motorized), Amount of work spent on manual weeding (days ha-1). The scores were assigned with a decision rule model built with DEXi software (see supplementary material)	Field monitoring network (Lairez et al., 2023)
ENVIRONMENT	
Control of herbicide leaching: Score based on direct measurement only for maize fields (10−100), aggregating 3 variables: herbicide treatment risk, leaching risk due to heavy rainfall in the 2 days following herbicide application, and leaching risk due to soil type. Further details in Lairez et al. (2023).	Field monitoring network (Lairez et al., 2023)
Maintenance of soil buffer capacity: Score based on direct measurement (10–100), aggregating 3 variables: Soil pH, soil cation exchange capacity and biomass left on soil surface. Further details in Lairez et al. (2023).	Field monitoring network (Lairez et al., 2023)
Control of erosion: Score based on direct measurement (10–100), aggregating 4 variables: number of days between ploughing and sowing, runoff risk and slope. Further details in Lairez et al. (2023).	Field monitoring network (Lairez et al., 2023)
Nitrogen Balance: Score based on direct measurement (10–100). Nmin + Nfert − Nuptake With Nmin = α*fn*Norg (Sattari et al., 2014; Janssen et al., 1990); $\alpha = 68$, fn = 0.25*(pH -3) if $4.3 < pH < 7$, fn = 1 if $pH > 7$, Norg in kg N ha^{-1}, 20 cm depth and Nuptake = Ya*21 *(21 is N (kg) taken up per ton of maize grain at 12% humidity.* Further details in Lairez et al. (2023).	Field monitoring network (Lairez et al., 2023)

Table 3

Farm types identified from the hierarchical clustering on 120 farms and number of farms selected from each type to build the farm model. An asterisk (*) indicates values significantly different from the overall mean (χ 2 –test, *p* value<0.05).

	Type 1 Lowest resource endowed LRE (47% of farms)	Type 2 medium resource endowed farm MRE (47% of farms)	Type 3 Highest resource endowed farm HRE (6% of farms)
Number of farms per type selected to build the model	8	6	2
Total cultivated area (ha)	2.6*	4.3	9.1
Paddy rice area (ha)	0.8*	1.4*	2.2*
Maize area (ha)	1.6 *	2.6*	4.6*
Family size (number of people living in the house)	4.2*	6.4*	6
Mouths to feed per worker	1.8	1.7	1.4
Cattle (units)	1*	2.7*	6.7*
Total number of farm equipment (seed drill, milling machine, threshing machine, shelling machine, rototiller, truck, motorbikes, and car)	3.4*	5*	7.5*

in SCEN1 (SCEN2–2, in Table 4). This means that even after an increase in production cost of between 38 and 59%, depending on the current maize cropping system (CMS) considered, AMS would be economically attractive compared to CMS for the majority of farms. This extra cost can be considered the maximum affordable additional cost for farmers to acquire or rent the best machinery for soil preparation and sowing of AMS. Considering the larger sample of 120 farms, this would mean that cultivating AMS would increase the net income of 76.5% of them, while satisfying farm constraints relative to cash, labour and land availability over time, and as compared to the current system.

The economic attractiveness of AMS was the highest for HRE farms and the lowest for MRE farms under all the scenarios (Fig. 3). In SCEN1, the simulated area under AMS did not exceed 50% of the area under CMS in the Baseline for two farms of MRE type (see Fig. 3.B): one farm having sloping land exclusively and one farm whose cash availability was strongly constraining. In SCEN2–3, 44% of the simulated farms cultivated AMS on >50% of the area of CMS in the Baseline (Table 4). The maximum production costs above which AMS were no longer selected in the model were between 493 and 715 USD ha-1 depending on the soil type and the farm (SCEN2–4), i.e. an additional cost of 200 USD ha-1 on top of the production cost used for AMS in SCEN1. This maximum production cost affordable for AMS also represented an additional cost of 324 to 428 USD ha^{-1} on top of the cost of CMS (depending on soil type).

As shown in Fig. 4, even at a very low selling price, maize either in AMS or CMS was highly competitive against the other options proposed in SCEN3 to simulated farms, namely rainfed rice (rice-fallow) and pasture. On average, across all farms, the threshold of maize selling price at which both CMS and AMS were not selected anymore in the simulation was 106 USD/ton and 94 USD/ton, respectively; which means a decrease of 38% and 45% compared to the price at the time of the study. SCEN3-CMS resulted in a reduction in farm income ranging from −1 to −20% compared to the baseline, and SCEN3-AMS in a reduction of farm income ranging from −3 to −26% compared to SCEN1 (Fig. 4).

In SCEN3 the model selected rice-fallow system on 62% of the farms, the 38% other farms being simulated with pasture replacing maize (data not shown). For LRE farms, SCEN3 resulted in two farms crossing down the poverty line of 1.9 USD/day/member (in red, Fig. 4). Moreover, for another LRE farm, the model failed to find a viable farm solution when maize price was decreased to 21 and 38% (in SCEN3-CMS and SCEN3-CMS) whereas smaller decreases had not resulted in maize crop replaced by rice-fallow system or pasture. This means that food and education needs of the household could not be met under scenario SCEN3 (rice-fallow system instead of maize) for this farm.

The highest negative impact of decreased maize price on income under SCEN3 was found for HRE farms, i.e. the relatively largest farms, with an average income decrease of −15% and − 22% in SCEN3-CMS and SCEN3-AMS respectively.

3.4. *Multicriteria assessment of current farm types' performance*

The simulated total farm income varied greatly in the baseline among the farms selected, ranging from 527 to 8565 USD/year (indicator No. 1 in Table 5). The LRE farm type was the only one with farms below the poverty line. For the LRE farm that was rice constrained, 71% of the income was generated by off-farm activities (indicator No. 6 in Table 5), and the income diversity score was the lowest of all farm types (indicator No. 4 in Table 5).

The labour productivity of farming (indicator No. 9 in Table 5) overcame the daily off-farm income of 7.3 USD/man-day for only the HRE farm and the LRE farm accessing to a small paddy field (7.4 USD/man-day).

Three simulated farms were unable to generate sufficient income to feed and educate an additional dependant (indicator No. 15 in Table 5), i.e. without falling below the 1.9 USD/day/capita poverty line (LRE rice constrained farm, LRE accessing to small paddy field and maize on sandy

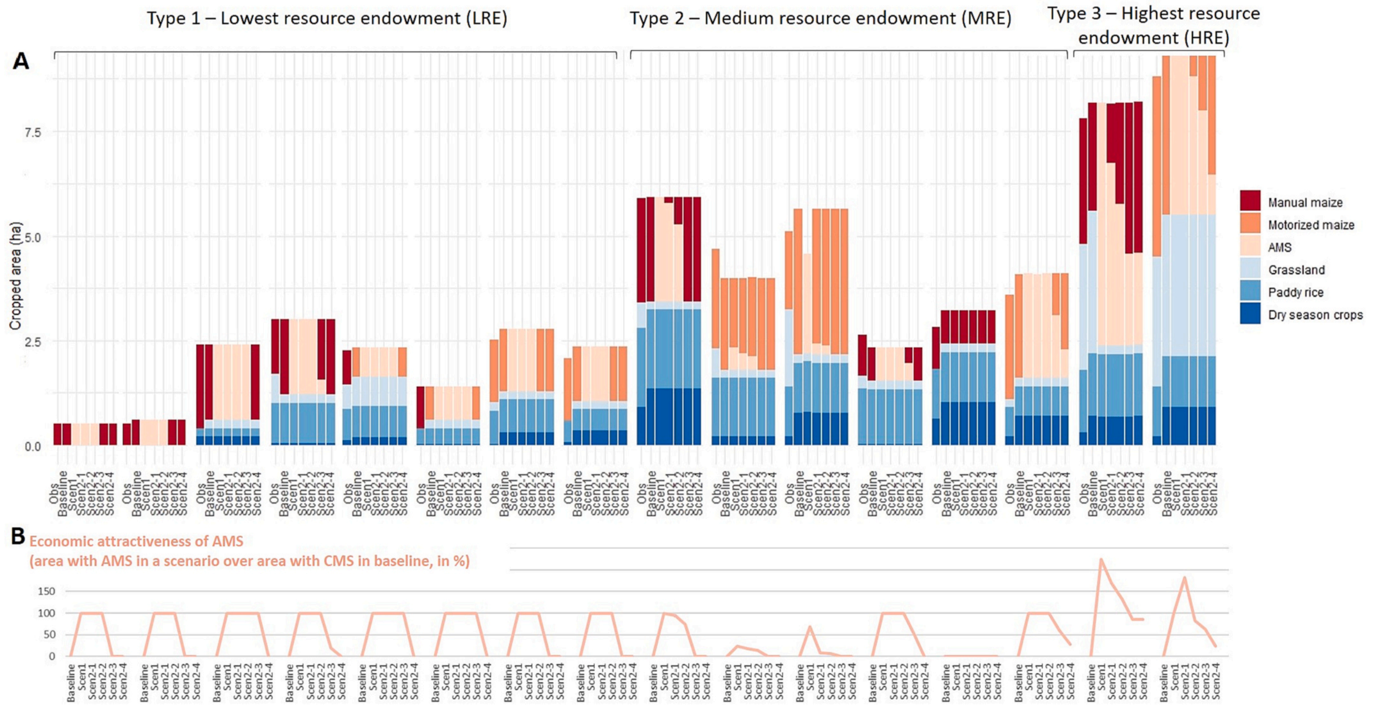


Fig. 3. Land allocation observed and simulated for the 16 farms used to build the model (3.A) and economic attractiveness of AMS (Alternative Management of maize Systems, with well mastered crop establishment obtained targeting yield gap closure and herbicide use reduction on different soil types) (3.B). Scenarios (Scen1 to Scen2–4) are simulations introducing AMS in the list of cropping system options available to the simulated farmers. "Manual maize" and "Motorized maize" are CMS, i.e. Current Management of maize Systems. Obs: Observed farm plan, Baseline: current farm optimized for income maximization under constraints, Scen2-i: sensitivity analysis of economic attractiveness of AMS to the production cost of AMS. In scen2-i the production cost of AMS was gradually increased by i*50 USD until AMS was no longer simulated for none of the farms (scen2–5, not shown on the figure).

soil, and MRE farm). Only the LRE rice constrained farm was not self-sufficient in rice (indicator No. 16 in Table 5). Workload peaks (indicator No. 17 in Table 5) were identified for the MRE and HRE farms, with 2 to 3 periods (out of 5) simulated with a workload peak.

Regarding the environmental indicators, every farm displayed in Fig. 5 used herbicide above recommended dose, leading to low herbicide scores, and particularly for farms with fertile clay loam soils (score of 22/100, indicator No. 25 in Table 5). Maintenance of soil buffer capacity was low on sandy soils, and erosion control was low on clayey soils (indicator No. 26 and 27 in Table 5, scores of 20/100 and 45/100, respectively). Nitrogen balance were low on every farm, but particularly on farms having sandy soils (indicator No. 28 in Table 5).

3.5. Effects of AMS on farms' performance

For 87% of the simulated farms, AMS did not generate a decline in farmers' income and in some cases even increased it significantly, while allowing the improvement of herbicide score, nitrogen balance and maintenance of soil buffer capacity (Fig. 5).

SCEN1 resulted in an increase of the following indicators on the different farms compared to the baseline (Table 5): total farm income (+14% for the LRE rice constrained farm and HRE farm), product from farm activities (ranging from +10% to +53% for all farm types), labour productivity from farming activities (ranging from +14% to +20% for LRE farm accessing to a small paddy field and MRE farm), number of affordable additional dependants (one additional dependant was simulated as affordable for MRE and HRE farms), work and ease of work (performance multiplied by 1.5 for two farms), herbicide score (performance increased for all farm types, multiplied by between 1.3 and 4.7), maintenance of soil buffer capacity (performance increased for all farm types, multiplied by between 1.3 and 1.6). SCEN1 also resulted in a marked increase of nitrogen balance indicator for farms having sandy soils (performance multiplied by 1.5).

However, for all farms SCEN1 decreased the performance of the criteria "control of erosion" and "cash and maize price dependency". The indebtedness rate increased, the highest indebtedness being 10.2% in SCEN1 for LRE farm accessing to a small paddy field. Moreover, even if the better management of maize, as represented by the shift from CMS to AMS in the farm model, increased the farm income for all farm types, it was not sufficiently to lift the strongly rice-constrained farm of LRE type out of extreme poverty. This is because under the baseline scenario this farm was cultivating CMS with a gross margin already as high as 69% of the gross margin of the corresponding AMS (CMS- *ManFertileSoil* in Table 1).

4. Discussion

4.1. High attractiveness of maize production despite its low sustainability

The first key result of this study is that maize production was economically attractive to farmers compared to the other options included in the optimisation model (pasture and rice-fallow system). This is demonstrated by the large decrease (−38%) in the price of maize that was necessary in our simulations to switch from maize to rice-fallow or pasture cropping systems. Under the resulting scenario without maize (SCEN3), farmers' income was well below the simulated current income and for one of the low resource endowed farms, survival was no longer guaranteed as the model could not find a viable solution to meet basic food and education needs of the household simulated. If maize price at farm gates in Laos follows global market trends that have increased for more than ten years, it is not expected to lower much compared to what was observed at the time of our surveys. This confirms that even with poor technical management for maize production and at a very low selling price, maize is clearly the main economic opportunity for the

Table 4

Economic attractiveness of AMS (maize cropping systems with reduced yield gap and herbicide use): simulated area with AMS in the scenario (SCEN1 or SCEN2) over simulated area with CMS in the baseline (in % of CMS area in the baseline). Standard deviation in brackets.

Scenarios	Economic attractiveness (%). Average, with standard deviation in ()	Percentage of farms with a simulated area of AMS >50% of the area of CMS in the baseline (%)
SCEN 1: 16 farms	107 (35)	87
Farm Type 1-LRE	100 (0)	100
Farm Type 2-MRE	92 (30)	67
Farm Type 3-HRE	203 (29)	100
Sensitivity analysis on production cost of AMS		
SCEN2–1: 16 farms	111 (29)	81
Farm Type 1-LRE	100 (0)	100
Farm Type 2-MRE	98 (3)	50
Farm Type 3-HRE	126 (63)	100
SCEN2–2: 16 farms	99 (13)	81
Farm Type 1-LRE	100 (0)	100
Farm Type 2-MRE	91 (15)	50
Farm Type 3-HRE	97 (49)	100
SCEN2–3: 16 farms	81 (31)	44
Farm Type 1-LRE	100 (0)	38
Farm Type 2-MRE	56 (5)	33
Farm Type 3-HRE	74	100
SCEN2–4: 16 farms	86 (0)	6
Farm Type 1-LRE	0	0
Farm Type 2-MRE	0	0
Farm Type 3-HRE	86	50

farmers of South East Asia in situations similar to that of our study, compared to their formerly predominating option of rainfed rice as well as to that of livestock based on improved pasture. Other cash crop opportunities are emerging in the region like tea, banana and chili (Paul et al., 2022), but were not included in this study due to a lack of robust estimation of their technical coefficients.

Counterbalancing this high economic attractiveness of maize production, we showed that most current farms performed relatively badly on several sustainability indicators compared to improved crop management. Our study identified an extreme case, the lowest resource endowed farm that was rice-constrained, for which each of our sustainability indicators was at a low level except for "control of erosion", "maintenance of soil buffer capacity" and "work and ease of work". This farm had a particularly low agricultural productivity, did not reach enough income to escape poverty (0.5 USD/capita/day) and had a very low performance on "control of herbicide leaching" indicator. Another farm performed the best on economic and agricultural productivity (3.4 USD/capita/day), but was the least performing on controlling herbicide leaching. Both examples tended to overuse relatively cheap herbicide to maximise as much production per hectare and work invested. Such cases of over-using inputs are typically found where farmers transitioned to new cropping systems with higher profits (Ahlheim et al., 2012; Fu et al., 2010; Rasmussen et al., 2018; van Vliet et al., 2012). Sustainable intensification was forged to answer to this challenge of optimizing the farming systems on both dimensions of protecting the environment and increasing agricultural productivity (Tilman et al., 2002; Pretty et al., 2011).

4.2. Reducing farms' negative impact on the environment is possible under certain conditions

The second key result was that the hypothetical alternative management of maize (AMS) we modelled to reduce herbicide use and increase yields were economically attractive to all farm types, albeit slightly less for farms having fertile soils or for those having strong cash constraints. More precisely, this economic attractiveness as we defined it in the material and methods section means that despite possibly increased labour or cash needs, AMS complies with farm constraints in terms of labour and cash availability across the different key periods of the year and in terms of providing resources for satisfying the basic needs (including food needs) of the households, and generates an increased income compared to the current maize management, and even more when compared to the rainfed rice system that was predominating a few decades ago or to replacing maize with improved pasture for livestock.

As exemplified in Fig. 5 for a selection of contrasted farms, AMS would lead to more income, productivity and less herbicide leaching risk. However, even if AMS was simulated "economically attractive", it would require more cash availability at the beginning of the cropping season, increase the indebtedness rate of farmers and increase erosion risk. Even with a maximum indebtedness rate simulated of 10%, this is still half the rate observed in the sub-region for other cash crops (Talerngsri-Teerasuwannajak and Pongkijvorasin, 2021). Short-term credit for maize cultivation to meet the production costs are common in the region (Bruun et al., 2017), however, farmers have to repay the credit after maize harvest with very high interests of 12% (at the time of the study). Regarding the increase of erosion risk, it resulted from two key choices we made and assumed in Lairez et al. (2023), when designing AMS: late sowing dates comparatively to the current practice and mechanical weeding instead of a chemical weeding method.

For farms with very limited land (<1 ha) and rice-constrained, the income still remained very low after simulation with alternative maize under the price system that was observed at the time of the study. Even if it was not the majority of the farms, such cases of constrained agriculture have also been encountered in other studies in the same province or the sub-region (Ritzema et al., 2019; Epper et al., 2020). Gérard et al. (2020), Ollenburger et al. (2018), Vanlauwe et al. (2014) also remarked in the sub-Saharan Africa context that realistic pathways toward sustainable intensification of mixed crop-livestock farms are not sufficient to lift out of poverty the numerous small farms that are currently under extreme poverty with their food security not ensured. Several studies highlighted financial constraints and risk aversion of poor farmers as the underlying causes of these farmers rarely adopting sustainable intensification technologies and particularly abusing of herbicides when available to them at low price (e.g. Ajayi et al., 2003; Jambo et al., 2019). Access to an additional half a hectare of lowland rice might multiply the income of this farm by 5 (results not shown). A solution sometimes invoked for this type of farms might be terracing non-irrigated land and set up irrigation channels for dry-season income. However, terracing is costly (2450 USD/ha, according to Wei et al. (2016) for a prevailing terrain slope of 10°), labour-intensive, and also has high maintenance costs.

To support farmers acquiring or renting a farm machinery more suitable to their soil constraints, and more generally to support them transitioning toward more profitable and less polluting practices, policy measures or an effective and fair credit system are required. This need of public support is reinforced by the current context on international

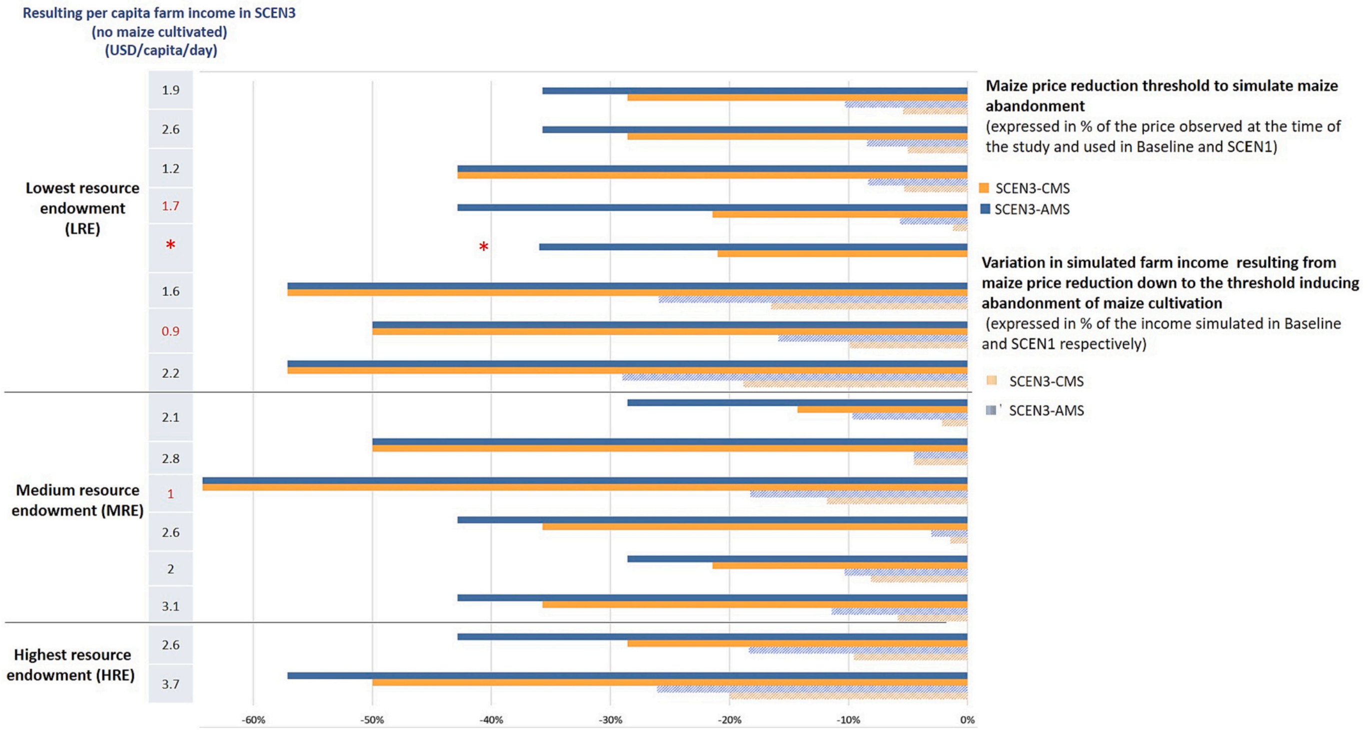


Fig. 4. Results of the scenario SCEN3 for the 16 farms, with SCEN3 representing simulations with a maize price level below which simulated farms abandoned maize cultivation (CMS or AMS), and replaced it with pasture or rice-fallow system. The left side of the graph displays the resulting per capita farm income per day. For each farm of the sample, the graph displays four bars, two continuous (upper part of the set of four) and two hatched bars (lower part of the set of four). The continuous bars display the reduction in maize price required to induce maize abandonment in the simulations or to induce an unfeasible farm plan (see the farm marked with an asterisk) and the hatched bars display the resulting decrease in farm income compared to the Baseline and SCEN1 scenarios used as a reference (SCEN3-CMS and SCEN3-AMS respectively). For two LRE farms and one MRE farm, SCEN3 resulted in a per capita farm income below the poverty line of USD 1.9/day (in red in the left column). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

markets. The price of maize has risen in the global cereal market since the time of the study (+89% from January 2017 to December 2022, according to IndexMundi, 2022a), and this is likely to continue given the current disruption and rising prices on global grain market. This could lead to an even higher economic attractiveness of maize production if local price follows the trend. However, input prices such as fertilizer or fuel are likely to continue to rise as well (IndexMundi, 2022b). With an increase in the selling price of maize up to 330 USD/ton (from 171 USD/ton at the time of the study), and despite concomitant multiplication by as high as 4 of the cost of NPK fertilizers, we calculated (not shown) that the gross margin of AMS could still increase between 17% and 105%, depending on the soil type. However, after such increase in fertilizers costs, cash requirements at the beginning of the cropping season would be multiplied between 1.5 and 2.5, representing a serious constraint for farms.

Another avenue of sustainable intensification as compared to our proposed improved maize management would be to consider conservation agriculture, to conciliate combating weeds (Teasdale et al., 1991) and reducing erosion risks (Lal, 1997). However not only the need to shift to seeders adapted to direct sowing in mulch would further increase the need for investment, but also large amounts of residues would have to be left on the soil to ensure that the weed combatting function of mulch is effective (Ranaivoson et al., 2017), meaning a trade-off with livestock production that currently makes use of these residues.

4.3. *Benefit of combining a farm model with multicriteria assessment of farm sustainability*

Our study shows the value of using farm modelling to contextualise field level results and capture the effects of the seasonality of farm activities and cash or labour constraint in farm level sustainability assessments. It also allows to identify the trade-offs that new options at field level may generate at farm level between sustainability indicators. A previous study at cropping system level (Lairez et al., 2023) had overestimated the economic benefits potentially brought by the prototypes of more sustainable maize-based cropping systems. For example, the largest farm which used a CMS with manual sowing, would double the labour productivity at field scale when switching to alternative maize. However, we found in the present study that this farm was constrained by family labour availability at the beginning of the cropping season and this prevented the farm to sow all its fields with maize in the simulations, leaving a substantial area under pasture, and resulting in an increase of labour productivity at farm scale of only 16%.

Farm models are often criticized for the overly simplistic way in which they represent the multiple objectives of farmers and the decision-making processes (see the review from Waldman et al., 2020). Actually, this proved to be a rather naïve view of the relative role of constraints and objectives in models based on “Mathematical Programming”, also named “Optimization Under Multiple Constraints”, because many things often seen as “farmer’s multiple objectives” are conveniently programmed as constraints in the model (Ceberio et al., 2018). For example, in our study, when we designed the constraints imposed in the model to the maximization of farm income, we ensured that they represented well goals of farmers as elicited using a best worst scaling experiment (a technique belonging to experimental economy, see Jourdain et al., 2022, for details).

A novel aspect of our study is that instead of opposing the multi-attribute approach based on indicators aggregated into criteria (Vasileiadis et al., 2013; Iocola et al., 2020; Craheix et al., 2012) with the integrated approach using farm models (see Janssen and van Ittersum, 2007 for a review), as in the review from Sadok et al., 2008, we used both, with the farm model itself contributing to the production of

Table 5

Comparison (SCEN1 vs. baseline) of raw values of sustainability indicators taken by three contrasted types of farm. In the baseline, only currently practiced maize systems CMS can be chosen by the model, whereas in SCEN1 AMS, i.e. Maize under improved management aiming at reducing yield gap and herbicide use are added to the list of options available to simulated farmers. Indicators marked with a star (*) are the ones used to assess the sustainability criteria in the diagrams displayed Fig. 5. T5: period 5 of dry season crops.

Farm type	Type 1-LRE Lowest resource endowed farm Rice constrained		Type 1-LRE Lowest resource endowed farm Small irrigated paddy				Type 2-MRE Medium resource endowed farm		Type 3-HRE Highest resource endowed farm	
Soil type on maize fields	**Fertile clay loam**		**Fertile clay loam**		**Sandy**		**Sandy and clay loam**		**Fertile clay loam**	
Scenarios										
(No.) Indicators	Baseline	SCEN1	Baseline	SCEN1	Baseline	SCEN1	Baseline	SCEN1	Baseline	SCEN1
Farm income & diversity										
(1) *Total farm income (USD)	527	599	3179	3451	2300	2464	4693	5037	8565	9888
(2) *Farm income/household Member per day (USD/member)	0.5	0.5	2.2	2.4	1.3	1.4	2.6	2.8	3.4	3.9
(3) *Cash-flow regularity (score)	3	3	5	5	5	5	5	5	5	5
(4) *Income diversity (score)	3	3	6	6	4	4	6	6	7	7
(5) Off-farm income plus weaving (USD)	673	673	774	774	910	910	1075	1075	2906	2846
(6) Ratio of off-farm income over total product (%)	71	67	14	9	21	19	17	11	21	13
(7) Cash income (total product) (USD)	943	1011	5484	8671	4368	4733	7446	12,399	14,049	21,192
Agricultural productivity										
(8) *Product from farm activities per hectare (USD/ha)	540	824	1874	2165	2524	2790	1624	1800	1490	1507
(9) *Labour productivity from farming activities (USD/man-day)	0	0	6.8	8.3	8	8.8	6.6	7.1	7.4	8.9
Cash and maize price dependency										
(10) * Cash outflow needed at the beginning of the cropping season (USD)	175	237	563	786	416	661	846	1452	1036	2053
(11) *Income dependency on maize price fluctuation (%)	10.3	13.7	6.1	8.5	3	6.5	4.9	8.2	3.3	9.6
Farm future viability										
(12) *Asset/child	0.3	0.6	1.2	1.5	0.3	0.3	0.9	0.9	1.2	1.5
(13) *Cattle unit/child	0	0	1.5	1.5	1.5	1.5	1.5	1.5	3.6	1.5
(14) *Land/child	0.4	0.4	0.9	0.9	0.4	0.4	1	1	2.2	2.2
(15) * Number of affordable additional dependants	0	0	1	1	0	0	0	1	4	5

Farm type	Type 1-LRE Lowest resource endowed farm Rice constrained		Type 1-LRE Lowest resource endowed farm Small irrigated paddy				Type 2-MRE Medium resource endowed farm		Type 3-HRE Highest resource endowed farm	
	Fertile clay loam		Fertile clay loam		Sandy		Sandy and clay loam		Fertile clay loam	
	Baseline	SCEN1	Baseline	SCEN1	Baseline	SCEN1	Baseline	SCEN1	Baseline	SCEN1
Rice production self-sufficiency										
(16) *Rice production self-sufficiency (–)	0	0	100	100	100	100	100	100	100	100
Work and ease of work										
(17) *Workload peak (%)	0	0	0	0	0	0	40	40	60	60
(18) *Ease of work (score 10–100)	41	100	41	100	100	100	96.4	100	41	100
(19) *Workload (%)	43.8	40.7	40.8	37.7	53	53	84.2	84.2	90.9	91.2
Farmer autonomy and constraints										
(20) *selling constraints (USD)	-149	–125	283	283	–538	–12	880	–538	1250	831
(21) *Lowland constraint to higher income (USD/ha)	4400	4400	758	758	819	819	1198	1198	1203	953
(22) *Non-irrigated land constraint to higher income (USD/ha)	354	489	367	429	8	428	220	367	352	317
(23) *Labour constraint to higher income (USD)	None	None	None	None	None	None	T5:4.4	T5:4.4	T5:4.4	T5:4.4
(24) *Indebtedness (%)	0.8	1.1	0	9.6	0.3	9.9	0	3.15	0	5.7
Control of herbicide leaching										
(25) *Herbicide score (10–100)	22	75	22	75	56	75	56	75	22	75
Maintenance of soil buffer capacity										
(26) * maintenance of soil buffer capacity score (0–100)	75	100	75	100	20	32	37	46	75	100
Control of erosion										
(27) *Erosion risk score (10–100)	77	10	77	10	49	10	52	12	77	10
Nitrogen balance										
(28) * Nitrogen balance (10–100)	54	54	54	54	25	50	35	54	54	54

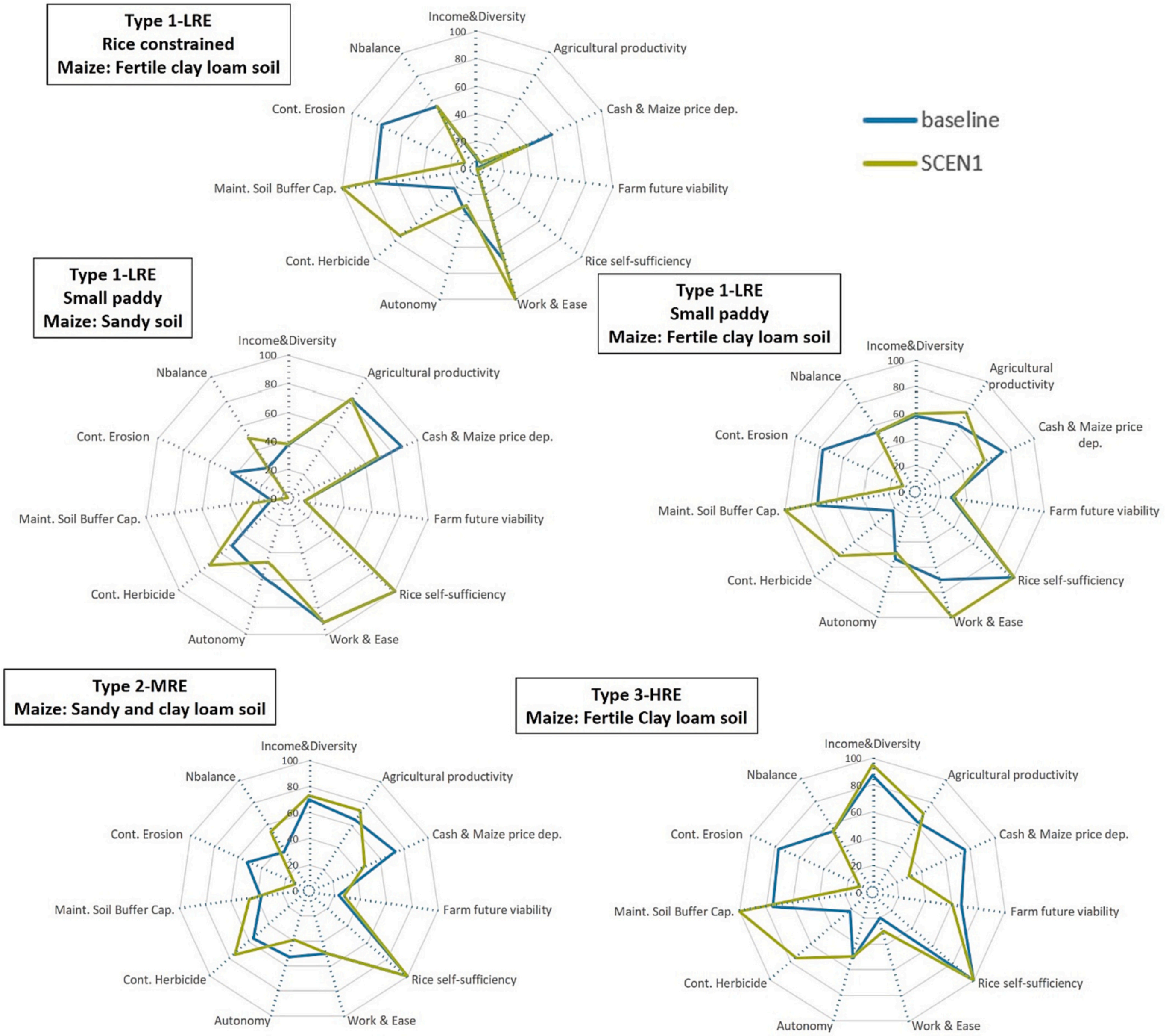


Fig. 5. Comparison of farms' performance on local sustainability criteria. The results were displayed for a representative farm of each farm type. In the case where a given farm type contained farms that cultivated maize on different soil types (Type 1-LRE), we selected a representative farm of the type per soil type. Further details on criteria and indicators' calculation are given Table 2. Type 1-LRE: lowest resource endowed farms, Type 2-MRE: medium resource endowed farms, Type 3-HRE: highest resource endowed farms.

indicators, and among them the farm level 'economic attractiveness' of improved crop management. This economic attractiveness indicator appears largely superior to the sole use of labour productivity and land productivity in a multicriteria assessment of complex farms. Labour and land productivity may be antagonist in such a way that no aggregation procedure based on them would allow deciding whether a prototype of cropping system could match the economic objectives of the farmer. And this would strongly limit the value of a sustainability assessment applied to farms of the developing world at the edge of survival. Furthermore, by capturing key interactions between activities mobilizing the main resources of the farm, the use of a farm model turns possible to update the assessment when changes occur in the economic environment of the farm, provided that data are available to document the new corresponding scenarios with an accuracy similar to that of the originally tested scenarios.

In our case study, once the improved crop management was identified as "economically attractive", a local sustainability assessment was performed. By using the Min-Max normalization of indicators to get dimensionless values, our method did not allow a comparison of performance on different criteria within the same farm type in a given scenario. To overcome this, we could have used locally derived optimums (López-Ridaura et al., 2002), by building a fictitious farm with all indicators at optimal levels as defined by a group of local stakeholders and experts.

Bioeconomic models often use dynamic crop models to generate the data needed by the farm model regarding crop agronomic and environmental performance (e.g. Humblot et al., 2017; Kuhn et al., 2020; Wolf et al., 2015). This was not necessary to make our case study conclusive, but it might be an avenue to more accurately estimate risks related to variations of crop performances across soils and climate in cases where such risks are likely to strongly constrain farm management (e.g. Affholder et al., 2006; Ricome et al., 2017). Unfortunately, available crop models are still relatively inaccurate in predicting the response of a maize crop to interacting nitrogen and water stresses under low input management in tropical areas, even in controlled environment without pests and diseases, due to insufficient experimental data to calibrate and adjust models that were predominantly developed by research teams of industrialized countries, with reference of the environment of these countries (Falconnier et al., 2020). The picture is certainly worse when it comes to accounting for weeds, that are a key factor of yield gap in family farms of the tropics especially under poor crop establishment and poorly mastered mechanized management (Affholder et al., 2003). Modelling the agronomic and environmental performances of complex, multi-cropping systems based on agroecological principles is in its infancy. There is therefore a need to strongly invest in crop modelling to allow progress in sustainability assessment of farms of the developing world using integrated approaches, especially if aiming at *ex-ante* assessment of hypothetical farming systems strongly based on agroecological principles. Meanwhile, the kind of approach we developed mixing multi-attribute and farm modelling approaches can help better assume the limits of current models while still benefiting of what it is most useful for, by capturing the interactions within the farm system that are the most determinant in farmers' decision.

5. Conclusion

Maize production is a very attractive activity for smallholder farms in South East Asia, but maize-based systems could be largely improved in their economic and environmental performance. Mixing multi-attribute with integrated assessment methods, our study shows that more sustainable maize cropping systems based on improved crop management could be economically attractive for a large diversity of farm households in a study region of northern Laos. Improved cropping systems management could improve agricultural productivity, farm income, soil quality, nitrogen balance and reduce herbicide leaching risks. However, improved crop management may imply higher risks of soil erosion due to mechanical weeding and later sowing date of maize for drought risk management. It also required more cash outflow at the beginning of the cropping season. This improved management was not economically attractive for only few farms operating on steep slopes or having high cashflow constraints.

Our study shows a case that may be of global relevance given the observed trends of rapid intensification of maize in family farms in lower-income countries. Our case study is an example of a region seeming biophysically favourable to intensive grain production, where family farms recently got out of subsistence farming, using conventionally intensified cropping systems leading to new threats to sustainability. While ambitious policies need to be implemented to support farmers toward agroecological intensification and simultaneously improve farmers' income and all environmental indicators (erosion, soil fertility, herbicide risks, and biodiversity) the development and scaling of improved maize based cropping systems through better crop management, attractive to farmers and with less negative effects, is needed. For this, enhancing cash availability in the hands of farmers at the beginning of the agricultural season will still be key toward sustainable intensification of agriculture in the case of maize production in Laos as well as in many other regions of the developing world were cash crops are being incorporated within traditionally subsistence farming systems.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgement

We thank the Department for Agricultural Land Management (DALaM) and the Provincial Agriculture and Forestry Organisation (PAFO) in Xieng Khouang for their support and assistance. We are grateful to the farmers in the villages of Xay, Leng and Nadou for their warm welcome. Many thanks to AR for her help on figure 1. This research was implemented as part of the Eficas project funded by the Directorate-General for Development and Cooperation - EuropeAid (EuropeAid/132-657/L/ACT/LA) and the *Agence Française de Développement* (Conservation Agriculture within the Northern Upland Development Programme, NUDP). Write-up and publication of this work was also supported by the OneCGIAR Global Initiative on Sustainable Intensification of Mixed Farming Systems (SI-MFS) (https://www.cgiar.org/initiative/mixed-farming-systems/). We are grateful to the 3 anonymous reviewers for their encouraging remarks and their useful comments and suggestions on a first version of our manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2023.103777.

References

Affholder, F., Scopel, E., Madeira Neto, J., Capillon, A., 2003. Diagnosis of the productivity gap using a crop model. Methodology and case study of small-scale maize production in Central Brazil. Agronomie 23, 305–325.

Affholder, F., Assad, E.D., Bonnal, P., Macena da Silva, F.A., Forest, F., Madeira Netto, J., Scopel, E., Corbeels, M., 2006. Risks of crop water stress in the Brazilian Cerrados from regional zoning to risk analysis at smallholders' level. Cahiers Agric. 15 (5), 433–439.

Affholder, F., Jourdain, D., Quang, D.D., Tuong, T.P., Morize, M., Ricome, A., 2010. Constraints to farmers' adoption of direct-seeding mulch-based cropping systems: a farm scale modeling approach applied to the mountainous slopes of Vietnam. Agric. Syst. 103, 51–62.

Ahlheim, Michael, Börger, Tobias, Frör, Oliver, 2012. The ecological price of getting rich in a green desert: A contingent valuation study in rural Southwest China. In: FZID Discussion Papers, No. 55-2012. http://nbn-resolving.de/urn:nbn:de:bsz:100-opus-7513.

Ajayi, O.C., Franzel, S., Kuntashula, E., Kwesiga, F., 2003. Adoption of improved fallow technology for soil fertility management in Zambia: empirical studies and emerging issues. Agrofor. Syst. 59, 317–326.

Akram-Lodhi, A.H., 2008. (Re)imagining agrarian relations? The world development report 2008: agriculture for development. Dev. Chang. 39, 1145–1161. https://doi.org/10.1111/j.1467-7660.2008.00511.x.

Alary, V., Corbeels, M., Alvarez, S., Soria, A., Valadares Xavier, J.H., da Silva, F.A.M., Scopel, E., 2016. Economic assessment of conservation agriculture options in mixed crop-livestock systems in Brazil using farm modelling. Agric. Syst. 144, 33–45.

Alary, V., Messad, S., Aboul-Naga, A., Osman, M.A., Abdelsabour, H., Salah, T., Juanes, X., 2020. Multi-criteria assessment of the sustainability of farming systems in the reclaimed desert lands of Egypt. Agric. Syst. 183, 102863.

Alexander, K.S., Millar, J., Lipscombe, N., 2010. Sustainable development in the uplands of Lao PDR. Sustain. Dev. 18, 62–70. https://doi.org/10.1002/sd.428.

Brentrup, F., Küsters, J., Kuhlmann, H., Lammel, J., 2004. Environmental impact assessment of agricultural production systems using the life cycle assessment methodology: I. theoretical concept of a LCA method tailored to crop production. Eur. J. Agron. 20 (3), 247–264.

Brodt, S., Six, J., Feenstra, G., Ingels, C., Campbell, D.S.A., 2011. Sustainable agriculture. Nat. Educ. Knowl. 3 (10), 1.

Bruun, T.B., de Neergaard, A., Burup, M.L., Hepp, C.M., Larsen, M.N., Abel, C., Aumtong, S., Magid, J., Mertz, O., 2017. Intensification of upland agriculture in Thailand: development or degradation? Land Degrad. Dev. 28 (1), 83–94.

Ceberio, M., Kosheleva, O., Kreinovich, V., 2018. Constraint approach to multi-objective optimization. In: Ceberio, M., Kreinovich, V. (Eds.), Constraint Programming and Decision Making: Theory and Applications. Springer International Publishing, Cham, pp. 21–25.

Craheix, D., Angevin, F., Bergez, J.-E., Bockstaller, C., Colomb, B., Guichard, L., Reau, R., Doré, T., 2012. MASC 2.0, un outil d'évaluation multicritère pour estimer la contribution des systèmes de culture au développement durable. Innov. Agronom. 20.

Cramb, R.A., Gray, G.D., Gummert, M., Haefele, S.M., Lefroy Rod, D.B., Newby, J.C., Stür, W., Warr, P., 2016. Trajectories of Rice-Based Farming Systems in Mainland Southeast Asia. Australian Centre for International Agricultural Research (ACIAR).

Ditzler, L., Komarek, A.M., Chiang, T.-W., Alvarez, S., Chatterjee, S.A., Timler, C., Raneri, J.E., Carmona, N.E., Kennedy, G., Groot, J.C.J., 2019. A model to examine farm household trade-offs and synergies with an application to smallholders in Vietnam. Agric. Syst. 173, 49–63.

Dogliotti, S., van Ittersum, M.K., Rossing, W.A.H., 2005. A method for exploring sustainable development options at farm scale: a case study for vegetable farms in South Uruguay. Agric. Syst. 86, 29–51.

Epper, C.A., Paul, B., Burra, D., Phengsavanh, P., Ritzema, R., Syfongxay, C., Groot, J.C. J., Six, J., Frossard, E., Oberson, A., Douxchamps, S., 2020. Nutrient flows and intensification options for smallholder farmers of the Lao uplands. Agric. Syst. 177, 102694. https://doi.org/10.1016/j.agsy.2019.102694.

Falconnier, G.N., Corbeels, M., Boote, K.J., Affholder, F., Adam, M., MacCarthy, D.S., Ruane, A.C., Nendel, C., Whitbread, A.M., Justes, É., Ahuja, L.R., Akinseye, F.M., Alou, I.N., Amouzou, K.A., Anapalli, S.S., Baron, C., Basso, B., Baudron, F., Bertuzzi, P., Challinor, A.J., Chen, Y., Deryng, D., Elsayed, M.L., Faye, B., Gaiser, T., Galdos, M., Gayler, S., Gerardeaux, E., Giner, M., Grant, B., Hoogenboom, G., Ibrahim, E.S., Kamali, B., Kersebaum, K.C., Kim, S.-H., van der Laan, M., Leroux, L., Lizaso, J.I., Maestrini, B., Meier, E.A., Mequanint, F., Ndoli, A., Porter, C.H., Priesack, E., Ripoche, D., Sida, T.S., Singh, U., Smith, W.N., Srivastava, A., Sinha, S., Tao, F., Thorburn, P.J., Timlin, D., Traore, B., Twine, T., Webber, H., 2020. Modelling climate change impacts on maize yields under low nitrogen input conditions in sub-Saharan Africa. Glob. Chang. Biol. 26, 5942–5964. https://doi.org/10.1111/gcb.15261.

Fu, Y., Chen, J., Guo, H., Hu, H., Chen, A., Cui, J., 2010. Agrobiodiversity loss and livelihood vulnerability as a consequence of converting from subsistence farming systems to commercial plantation-dominated systems in Xishuangbanna, Yunnan, China: A household level analysis. Land Degrad. Dev. 21, 274–284. https://doi.org/10.1002/ldr.974.

Gérard, F., Affholder, F., Mane, N.F., Sall, M., 2020. Impact de différentes politiques publiques sur l'intensification agroécologique et les inégalités de revenu dans le Bassin arachidier du Sénégal, Impact de différentes politiques publiques sur l'intensification agroécologique et les inégalités de revenu dans le Bassin arachidier du Sénégal, Agence française de développement, pp. 1–76.

Hammond, J., van Wijk, M., Teufel, N., Mekonnen, K., Thorne, P., 2021. Assessing smallholder sustainable intensification in the Ethiopian highlands. Agric. Syst. 194, 103266.

Hani, F., Braga, F., Stampfli, A., Keller, T., Fischer, M., Porsche, H., 2003. RISE, a tool for holistic sustainability assessment at the farm level. In: International Food and Agribusiness Management Review, 06.

Humblot, P., Jayet, P.-A., Petsakos, A., 2017. Farm-level bio-economic modeling of water and nitrogen use: calibrating yield response functions with limited data. Agric. Syst. 151, 47–60. https://doi.org/10.1016/j.agsy.2016.11.006.

IndexMundi, 2022a. Comodity prices of maize. Retrieved from. https://www.indexmundi.com/commodities/?commodity=corn&months=240 (access date: 27/02/2023).

IndexMundi, 2022b. Commodity prices (Urea). Urea Monthly Price - US Dollars per Metric Ton. Retrieved from. https://www.indexmundi.com/commodities/?commodity=urea&months=240 (access date: 27/02/2023).

Iocola, I., Angevin, F., Bockstaller, C., Catarino, R., Curran, M., Messéan, A., Schader, C., Stilmant, D., Van Stappen, F., Vanhove, P., Ahnemann, H., Berthomier, J., Colombo, L., Dara Guccione, G., Mérot, E., Palumbo, M., Virzì, N., Canali, S., 2020. An actor-oriented multi-criteria assessment framework to support a transition towards sustainable agricultural systems based on crop diversification. Sustainability 12, 5434.

Jambo, I.J., Groot, J.C.J., Descheemaeker, K., Bekunda, M., Tittonell, P., 2019. Motivations for the use of sustainable intensification practices among smallholder farmers in Tanzania and Malawi. NJAS - Wageningen J. Life Sci. 89, 100306.

Janssen, S., van Ittersum, M.K., 2007. Assessing farm innovations and responses to policies: a review of bio-economic farm models. Agric. Syst. 94, 622–636.

Janssen, B.H., Guiking, F.C.T., van der Eijk, D., Smaling, E.M.A., Wolf, J., van Reuler, H., 1990. A system for quantitative evaluation of the fertility of tropical soils (QUEFTS). Geoderma 46 (4), 299–318.

Jourdain, D., Lairez, J., Affholder, F., 2022. Identify Lao farmers' goals and their ranking using best–worst scaling experiment and scale-adjusted latent class models. J. Multi-Criteria Decis. Anal. 1–14 https://doi.org/10.1002/mcda.1785.

Kallio, M.H., Hogarth, N.J., Moeliono, M., Brockhaus, M., Cole, R., Waty Bong, I., Wong, G.Y., 2019. The colour of maize: visions of green growth and farmers perceptions in northern Laos. Land Use Policy 80, 185–194.

Keil, A., Saint-Macary, C., Zeller, M., 2008. Maize Boom in the Uplands of Northern Vietnam : Economic Importance and Environmental Implications. Discussion Paper.

Kuhn, T., Enders, A., Gaiser, T., Schäfer, D., Srivastava, A.K., Britz, W., 2020. Coupling crop and bio-economic farm modelling to evaluate the revised fertilization regulations in Germany. Agric. Syst. 177, 102687. https://doi.org/10.1016/j.agsy.2019.102687.

Kyeyune, V., Turner, S., 2016. Yielding to high yields? Critiquing food security definitions and policy implications for ethnic minority livelihoods in upland Vietnam. Geoforum 71, 33–43.

Lairez, J., Feschet, P., Aubin, J., Bockstaller, C., Bouvarel, I., 2016. Agriculture et développement durable: Guide pour l'évaluation multicritère (Educagri Editions).

Lairez, J., Lopez-Ridaura, S., Jourdain, D., Falconnier, G.N., Lienhard, P., Striffler, B., Syfongxay, C., Affholder, F., 2020. Context matters: agronomic field monitoring and participatory research to identify criteria of farming system sustainability in South-East Asia. Agric. Syst. 182, 102830.

Lairez, J., Affholder, F., Scopel, E., Leudpanhane, B., Wery, J., 2023. Sustainability assessment of cropping systems: a field-based approach on family farms. Application to maize cultivation in Southeast Asia. Eur. J. Agron. 143, 126716 https://doi.org/10.1016/j.eja.2022.126716.

Lal, R., 1997. Long-term tillage and maize monoculture effects on a tropical Alfisol in western Nigeria. II. Soil chemical properties. Soil Tillage Res. 42, 161–174.

Lestrelin, G., 2016. Land use change analysis in Xieng Khouang Province (1973-2016): Informing agro-ecological innovation processes. PAFO-LURAS-TABI multi-stakeholder meeting, Kham district, 11th March 2016. Retrieved from. https://www.eficas-laos.net/resources/communications-and-posters/20162 (access date: 29/09/2023).

Lestrelin, G., Kiewvongphachan, X., 2017. A Decade of Livelihood and Land Use Changes in Maize Production Areas of Sayaboury and Xieng Khouang Provinces: Implications for the Agroecological Transition. Eficas NUDP/CA, Vientiane, Lao PDR.

Lienhard, P., Dangé, G., Talon, M.P., Sosomphou, T., Syphanravong, S., 2004. Diagnostic agro-socio-economique de la zone d'intervention du Projet (Districts de Pek, Kham et Nonghet) : Programme national agroécologie (PRONAE), Province de Xieng Khouang. PRONAE, Vientiane, Laos.

López-Ridaura, S., Masera, O., Astier, M., 2002. Evaluating the sustainability of complex socio-environmental systems. The MESMIS framework. Ecol. Indic. 2, 135–148.

Luckmann, J., Ihle, R., Kleinwechter, U., Grethe, H., 2015. Do Vietnamese upland farmers benefit from high world market prices for maize? Agric. Econ. 46, 1–11. https://doi.org/10.1111/agec.12194.

Meul, M., Van Passel, S., Nevens, F., Dessein, J., Rogge, E., Mulier, A., Van Hauwermeiren, A., 2008. MOTIFS: a monitoring tool for integrated farm sustainability. Agron. Sustain. Dev. 28 (2), 321–332.

Norton, R.D., Hazell, P.B., 1986. Mathematical Programming for Economic Analysis in Agriculture. Macmillan.

Ollenburger, M., Crane, T., Descheemaeker, K., Giller, K.E., 2018. Are farmers searching for an african green revolution? Exploring the solution space for agricultural intensification in southern Mali. Exp. Agric. 55, 288–310.

Paul, B.K., Epper, C.A., Tschopp, D.J., Long, C.T.M., Tungani, V., Burra, D., Hok, L., Phengsavanh, P., Douxchamps, S., 2022. Crop-livestock integration provides opportunities to mitigate environmental trade-offs in transitioning smallholder agricultural systems of the Greater Mekong Subregion. Agric. Syst. 195, 103285.

Pollesch, N.L., Dale, V.H., 2016. Normalization in sustainability assessment: methods and implications. Ecol. Econ. 130, 195–208.

Pretty, J., 2008. Agricultural sustainability: concepts, principles and evidence. Philos. Trans. R. Soc. B 363 (1491), 447–465.

Pretty, J., Toulmin, C., Williams, S., 2011. Sustainable intensification in African agriculture. Int. J. Agric. Sustain. 9, 5–24. https://doi.org/10.3763/ijas.2010.0583.

Ranaivoson, L., Naudin, K., Ripoche, A., Affholder, F., Rabeharisoa, L., Corbeels, M., 2017. Agro-ecological functions of crop residues under conservation agriculture. A review. Agron. Sustain. Dev. 37, 26. https://doi.org/10.1007/s13593-017-0432-z.

Rasmussen, L.V., Coolsaet, B., Martin, A., Mertz, O., Pascual, U., Corbera, E., Dawson, N., Fisher, J.A., Franks, P., Ryan, C.M., 2018. Social-ecological outcomes of agricultural intensification. Nat. Sustain. 1, 275–282. https://doi.org/10.1038/s41893-018-0070-8.

Ricome, A., Affholder, F., Gérard, F., Muller, B., Poeydebat, C., Quirion, P., Sall, M., 2017. Are subsidies to weather-index insurance the best use of public funds? A bio-economic farm model applied to the Senegalese groundnut basin. Agric. Syst. 156, 149–176.

Ritzema, R.S., Douxchamps, S., Fraval, S., Bolliger, A., Hok, L., Phengsavanh, P., Long, C. T.M., Hammond, J., van Wijk, M.T., 2019. Household-level drivers of dietary diversity in transitioning agricultural systems: evidence from the Greater Mekong Subregion. Agric. Syst. 176, 102657. https://doi.org/10.1016/j.agsy.2019.102657.

Sadok, W., Angevin, F., Bergez, J.E., Bockstaller, C., Colomb, B., Guichard, L., Reau, R., Dore, T., 2008. Ex ante assessment of the sustainability of alternative cropping systems: implications for using multi-criteria decision-aid methods. A review. Agron. Sustain. Dev. 28 (1), 163–174.

Sattari, S.Z., van Ittersum, M.K., Bouwman, A.F., Smit, A.L., Janssen, B.H., 2014. Crop yield response to soil fertility and N, P, K inputs in different environments: testing and improving the QUEFTS model. Field Crop Res. 157, 35–46.

Shattuck, A., 2021. Risky subjects: Embodiment and partial knowledges in the safe use of pesticide. Geoforum 123, 153–161.

Talerngsri-Teerasuwannajak, K., Pongkijvorasin, S., 2021. Agricultural business model and upland sustainability: evidence from northern Thailand. Curr. Res. Environ. Sustain. 3, 100085.

Teasdale, J.R., Beste, C.E., Potts, W.E., 1991. Response of weeds to tillage and cover crop residue. Weed Sci. 39, 195–199.

The Montpellier Panel, 2013. Sustainable Intensification: A New Paradigm for African Agriculture. Agriculture for impact, London.

Tilman, D., Cassman, K.G., Matson, P.A., Naylor, R., Polasky, S., 2002. Agricultural sustainability and intensive production practices. Nature 418, 671–677. https://doi.org/10.1038/nature01014.

Timler, C., Alvarez, S., DeClerck, F., Remans, R., Raneri, J., Estrada Carmona, N., Mashingaidze, N., Abe Chatterjee, S., Chiang, T.W., Termote, C., Yang, R.-Y., Descheemaeker, K., Brouwer, I.D., Kennedy, G., Tittonell, P.A., Groot, J.C.J., 2020. Exploring solution spaces for nutrition-sensitive agriculture in Kenya and Vietnam. Agric. Syst. 180, 102774.

Vanlauwe, B., Coyne, D., Gockowski, J., Hauser, S., Huising, J., Masso, C., Nziguheba, G., Schut, M., Van Asten, P., 2014. Sustainable intensification and the African smallholder farmer. Curr. Opin. Environ. Sustain. 8, 15–22. https://doi.org/10.1016/j.cosust.2014.06.001.

Vasileiadis, V.P., Moonen, A.C., Sattin, M., Otto, S., Pons, X., Kudsk, P., Veres, A., Dorner, Z., van der Weide, R., Marraccini, E., Pelzer, E., Angevin, F., Kiss, J., 2013. Sustainability of European maize-based cropping systems: economic, environmental and social assessment of current and proposed innovative IPM-based systems. Eur. J. Agron. 48, 1–11.

van Vliet, N., Mertz, O., Heinimann, A., Langanke, T., Pascual, U., Schmook, B., Adams, C., Schmidt-Vogt, D., Messerli, P., Leisz, S., Castella, J.-C., Jørgensen, L., Birch-Thomsen, T., Hett, C., Bech-Bruun, T., Ickowitz, A., Vu, K.C., Yasuyuki, K., Fox, J., Padoch, C., Dressler, W., Ziegler, A.D., 2012. Trends, drivers and impacts of changes in swidden cultivation in tropical forest-agriculture frontiers: a global assessment. Glob. Environ. Chang. 22, 418–429. https://doi.org/10.1016/j.gloenvcha.2011.10.009.

Vongvisouk, T., Mertz, O., Thongmanivong, S., Heinimann, A., Phanvilay, K., 2014. Shifting cultivation stability and change: contrasting pathways of land use and livelihood change in Laos. Appl. Geogr. 46, 1–10.

Waldman, K.B., Todd, P.M., Omar, S., Blekking, J.P., Giroux, S.A., Attari, S.Z., Baylis, K., Evans, T.P., 2020. Agricultural decision making and climate uncertainty in developing countries. Environ. Res. Lett. 15, 113004. https://doi.org/10.1088/1748-9326/abb909.

Wei, W., Chen, D., Wang, L., Daryanto, S., Chen, L., Yu, Y., Lu, Y., Sun, G., Feng, T., 2016. Global synthesis of the classifications, distributions, benefits and issues of terracing. Earth Sci. Rev. 159, 388–403. https://doi.org/10.1016/j.earscirev.2016.06.010.

Wolf, J., Kanellopoulos, A., Kros, J., Webber, H., Zhao, G., Britz, W., Reinds, G.J., Ewert, F., de Vries, W., 2015. Combined analysis of climate, technological and price changes on future arable farming systems in Europe. Agric. Syst. 140, 56–73. https://doi.org/10.1016/j.agsy.2015.08.010.