Context matters: Agronomic field monitoring and participatory research to identify criteria of farming system sustainability in South-East Asia.

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Abstract

In the mountainous areas of South-East Asia, family farms have shifted from subsistence to input-intensified and market-oriented maize-based farming systems, resulting in a substantial increase in farm income, but also in new environmental threats: deforestation, biodiversity loss, soil erosion, herbicide leaching and soil fertility degradation. In this typical case study of cash-strapped farms, where the balance between socio-economic and environmental dimensions of sustainability is complex, we used participatory methods (serious games and Q-methodology), combined with agronomic field monitoring, to identify relevant farm and field-level criteria for sustainability assessment.

Serious games at farm level showed that short-term socio-economic dimensions prevailed over environmental dimensions in farmers' objectives. However, farmers also greatly valued their capacity to transfer a viable farm to the next generation and avoid herbicide use. Serious games at field level showed that some farmers were willing to preserve soil fertility for future generations. The agronomic field monitoring showed that maize yield deviations from potential water-limited yield were primarily due to weed infestation favoured by low sowing density, due to uncontrolled moto-mechanized crop establishment. This technical failure at the beginning of the maize cycle led to herbicide overuse, poor returns on investment for fertilizer, and increased exposure to soil erosion.

Combining the perspectives of scientists and farmers led to the following set of locally-relevant criteria: i) at farm level: farm income, diversity of activities, farmer autonomy, farmer health, workload peaks, soil fertility transfer between agroecological zones in the landscape, rice and forage self-sufficiency; ii) at field level: resource use efficiency, soil fertility, erosion and herbicide risks, susceptibility to pests, weeds and climate variability, biodiversity, land productivity, economic performance, labour productivity and work drudgery. Our approach helped to identify key relevant sustainability criteria and could be useful for designing alternatives to current maize-based cropping systems, and contributed to informing priority-setting for institutional development and agricultural policies in the region.

Keywords: sustainability, multi-criteria assessment, classification and regression tree, serious games, maize yield gap, Laos.

1. Introduction

In recent decades, the productivity and income of smallholder farmers have increased considerably in South-East Asia, thanks to greater market integration (Drahmoune, 2013). The changes in farming systems followed a conventional intensification pathway that mimicked the Green Revolution. Non-irrigable highlands were rapidly converted to maize mono-cropping (Kong *et al.*, 2019), driven mostly by the high profitability of animal feed production for a growing meat market. Despite these trends, farmers in Laos are still constrained by cash and labour availability (Jourdain *et al.,* 2020). The shift from subsistence to input-intensified and market-oriented farming systems casts doubts upon farming system sustainability, in relation to (i) economic threats such as input/output price volatility and farmer indebtedness (Hepp *et al.*, 2019) and (ii) environmental threats linked to deforestation, biodiversity loss, soil erosion, herbicide leaching and soil fertility degradation (Tivet *et al.*, 2017; Shattuck, 2019; Dupin *et al.*, 2009).

The sustainability concept is multidimensional and embodies ecological, economic and social dimensions (Hansen, 1996; Binder et al., 2010). Analysing farming system sustainability in South-East Asia along these dimensions is crucial for taking up the challenges ahead for these farming systems, and for identifying their strengths and weaknesses. In developing countries sustainable agriculture embodies natural resource and ecosystem preservation, enhances resiliency to change and is the driver for improving food security and poverty reduction (Schindler *et al.*, 2015; Schader *et al.*, 2014). Poor smallholder farmers are expected to face trade-offs between short-term socio-economic objectives (e.g. income, food security) and long-term environmental objectives (e.g. soil fertility, water pollution by pesticides) (Shiferaw and Holden, 1998; Lipton, 1997). This calls for an integrated assessment of farming systems that quantifies the trade-offs between socio-economic and environmental dimensions across a set of criteria, to explore the sustainability of agricultural changes (Ness *et al.*, 2007). By "criteria", we mean the issues, themes, principles, goals, "abstract indicators", or attributes describing the sustainability of agricultural systems (different uses of terminology are described in Reed *et al.*, 2006; Binder *et al.*, 2010; Niemeijer and de Groot, 2008; de Olde *et al.*, 2016; van Cauwenbergh *et al.*, 2007). Criteria are not directly measurable, but they link sustainability dimensions to quantifiable indicators. Multi-criteria tools are used to compare alternatives (e.g. different cropping or farming systems) against a set of criteria for decision-support (Boggia and Cortina, 2010; Wolfslehner *et al.*, 2012; Sadok *et al.*, 2008). Multi-criteria sustainability assessment is a useful approach when there are multiple, non-commensurate, and possibly conflicting criteria (Alrøe *et al.*, 2016). Numerous systemic and generic multi-criteria tools have been developed to assess farming system sustainability (see, for example, some indicator-based tools at farm level: 4Agro (Bertocchi *et al.*, 2016), IDEA (Zahm *et al.*, 2019), APOIA-NovoRural (Stachetti Rodrigues *et al.*, 2010), MOTIFS (Meul *et al.*, 2008), SAFE (van Cauwenbergh *et al.*, 2007), RISE (Häni *et al.*, 2003)). Most of the existing approaches assess farming systems against a set of criteria meant to be universal. As such, generic tools often contain preconceived ideas of sustainability (Bosshard, 2000) and usually overlook the contextual prioritization emphasized in local sustainability assessments (Barbier and López-Ridaura, 2010; Gasparatos, 2010; Gasparatos *et al.*, 2008). Sustainability is a matter of perspective and relevant criteria often depend on the local context (Zhen and Routray, 2003; Reed *et al.*, 2006; Bond *et al.*, 2011; Lairez *et al.*, 2016; Lele and Norgaard, 1996). For example, in a case study of Danish maize value chains for German biogas, Gasso *et al.* (2015) compared key sustainability criteria identified by stakeholders with criteria identified in generic frameworks. They showed that the generic frameworks covered context-specific environmental issues, but not context-specific socio-economic issues. Other sustainability assessment methods overcome this weak point by considering farmer and/or stakeholder perspectives to select evaluation criteria (e.g. Roy *et al.*, 2013; Coteur *et al.*, 2016; Coteur *et al.*, 2018; López-Ridaura *et al.*, 2002; Ssebunya *et al.*, 2016; Yegbemey *et al.*, 2014; Sydorovych and Wossink, 2008). Farmers are the key decision-makers, so their perspective is essential. However, data collected from interviews alone are often inadequate for quantifying and understanding sustainability issues (Fraser *et al.*, 2006). Moreover, the span of a farmer's perspective can be incomplete in times of rapid change (Klapwijk *et al.*, 2014).

Expert advice and literature can also help inform the choice of quantitative verifiable criteria. However, the scientific perspective of experts is not "pure knowledge" without assumptions, values or preferred fields of interest (Sala *et al.*, 2015). de Olde *et al.* (2017) showed that experts disagreed about what was reliable knowledge for assessing sustainability and Smith *et al.* (2017) highlighted a disagreement in the research community over the relevant indicators for assessing sustainability. Scientists have specific worldviews that generate subjectivity in the evaluation (Lele and Norgaard, 1996). There is therefore a need to go beyond expert and scientist consultations to select sustainability criteria using an explicit procedure (Bosshard, 2000). The literature provides only a few examples where the scientist knowledge used in generic frameworks goes beyond expert consultation to select criteria and is based on a quantitative monitoring design (Reed, 2005). A selection of relevant sustainability criteria with a transparent scientific diagnosis is needed, with a view to understanding interconnected biophysical processes, especially in data-scarce regions.

In order to identify criteria and strengthen the dialogue to foster the co-designing of more sustainable farming systems, it is necessary to bring together the perspectives of both farmers and scientists, because the perspectives of farmers and scientists taken separately are incomplete for dealing with complex sustainability issues. Mixed-method approaches that combine quantitative and qualitative information are helpful in enhancing the understanding of sustainability issues, by providing multiple ways of viewing a problem (Bond *et al.*, 2011; Gough *et al.*, 1998; Creswell and Clark, 2017), and in allowing the strengths of one method to offset the weaknesses of others (Creswell and Clark, 2017). The literature is scant on how the knowledge of farmers and scientists can be combined to narrow the set of relevant sustainability criteria before an assessment (see Reed *et al.,* 2006 for a useful example). Most existing approaches integrating farmer and scientist perspectives for sustainability assessment seek to select indicators to assess a predefined set of criteria, assuming that sustainability is a generic concept defined with universal criteria.

The objective of our study was to identify relevant criteria for a sustainability assessment of farming systems in northern Laos, with specific emphasis on combining farmer and scientist perspectives and documenting how the criteria were chosen. The set of criteria identified would be the first step for then defining, in a later study, some specific indicators to be quantified for analysing the conditions under which maize cultivation can be sustainable for different farm types in the region. The specific objectives of this study were to (i) identify farmers' objectives and to understand their priorities and perceptions with regard to sustainability, for farm-level strategic resource allocation and plot-level tactical crop management, by way of serious games and Q-methodology, (ii) identify the determinants and criteria of maize cropping system sustainability through a plot-level scientific agronomic diagnosis, and (iii) aggregate farmers' perspectives and insights from the agronomic diagnosis into a set of sustainability criteria that could inform multi-criteria sustainability assessment. The region of Xieng Khouang province in northern Laos was chosen as a typical case study of the market integration of farming systems.

2. Methods

In what follows, we start by describing the overall approach and the study sites (2.1 and 2.2), followed by the methods employed to (i) capture farmers' perceptions of sustainability and (ii) gather scientific insights on sustainability.

2.1. Overview of the method

To inform the selection of locally relevant and scientifically sound criteria for sustainability assessment, we combined different approaches and methods. Serious games were used to identify farmers' objectives (see section 2.3.), Q-methodology was applied to better understand farmers' perceptions of soil fertility (see section 2.3.) and an agronomic diagnosis was used to identify factors determining the agronomic and environmental performance of crop management (see section 2.4.) (Figure 1). At the end of each step described below, i.e. serious games, Q-methodology and agronomic diagnosis, outputs were summarized into lists of criteria. Eventually, these lists were aggregated into a final list of sustainability criteria.

We carried out a card game in four villages (Lé, Xay, Leng and Dokham) and a group game in three villages (Lé, Xay and Leng). Q-methodology was implemented in four villages that captured farm and soil type variability (Lé, Leng, Nadou and Xay). Field monitoring for the agronomic diagnosis was set up in three villages (Xay, Nadou and Leng) covering an area of 7 km^2 (Figure S1). The villages of Lé, Leng and Dokham were selected because an exhaustive agricultural census was available describing all farm households using basic variables (cropped areas, head of cattle and number of people per family). The villages of Xay and Nadou had soils with a high sand content and were added to increase the representativeness of soil type variability.

2.2. Site description

We selected the Kham district in Xieng Khouang province located in northern Laos, close to the Vietnamese border (19°38’N, 103°33E; 605 m above sea level) (Figure S1, Supplementary material) as a typical case of the market integration of farming systems with the commercialisation of hybrid maize. Over the past two decades, farmers have switched from extensive manually cultivated upland rice systems to cash crop systems with hybrid maize cultivation, combined with the use of moto-mechanization, herbicides and mineral fertilizers. This rapid switch to maize cultivation was favoured by the increase in maize prices and in the demand for maize from the thriving livestock feed industry in Vietnam in the 2000s. Today, rural development stakeholders in northern Laos commonly believe that maize cultivation is not sustainable and refer to it as ‘resource-mining’ agriculture with a negative impact on the environment, i.e. leading to increased soil erosion, loss of soil fertility and chemical pollution (Bartlett, 2016; ACIAR, 2014; Julien *et al.*, 2008). In the peer-reviewed literature for Laos, maize cultivation was found to increase production costs (Luangduangsitthideth *et al.*, 2018) and soil erosion (Dupin *et al.* 2009). In Thailand, Bruun *et al.* (2017) found that maize cultivation had an impact on soil quality. Other studies, analysing farmer perceptions and practices in Laos and the subregion, showed that maize might increase environmental degradation (Kallio *et al.*, 2019; Southavilay *et al.*, 2012; Tuan *et al.*, 2014; Epper *et al.*, 2020; Shattuck, 2019). There is nevertheless limited empirical evidence to support claims of environmental degradation (Lestrelin, 2010).

Our case study was located in the Kham basin, an area of Kham district where maize has spread very rapidly because of relatively fertile and flat valleys with moderate elevation and slopes (500 to 600 m asl). Lowlands are dedicated to rice cultivation and uplands to forest, pastures and maize cultivation. Hybrid maize is sown once a year during the rainy season (May-October) in sole stands without rotation with other crops. Cultivation starts in early April with tillage services using tractors equipped with a disc plough. Maize is either sown manually with two seeds in a hole made with a digging stick, or mechanically with a seed drill mounted on the rototiller used for paddy rice preparation. If applied, compound (NPK 16-20-0) mineral fertilizer is used. The herbicides commonly used are atrazine (1-Chloro-3-ethylamino-5-isopropylamino-2,4,6-triazine), paraquat (1,1'-Dimethyl-4,4'-bipyridinium dichloride), and glyphosate (*N*-(phosphonomethyl)glycine). Europe banned atrazine in 2003. Paraquat was banned in Laos in 2011, but is still sold on local markets by small retailers (Vázquez *et al.*, 2013; Shattuck, 2019).

2.3. Farmer perspective: serious games and Q-methodology

We used two types of serious games to reveal farmers' objectives. The participation level was consultative (Barreteau *et al.*, 2010). Serious games can reveal more salient information than direct household interviews (Cash *et al.*, 2003). Farmers' objectives are connected to two levels of decision-making: (i) farm-level strategic resource allocation and (ii) plot-level tactical crop management. We first played an individual card game to identify farmers' objectives (farm level), and then a group game to identify farmers' important attributes for deciding which crop to grow (field level). The impact on soil fertility emerged as an important attribute during the group game. We therefore used a Q-methodology survey (Alexander *et al.* (2018) and Pereira *et al.*, (2016)) to deepen our understanding of farmers' perception of soil fertility.

Individual card game to determine famers' objectives

The aim of the individual card game, designed by the authors, was to reveal farmers' main objectives at farm level with a five-year perspective. Following the approach of Berbel and Rodriguez-Ocana (1998), we related farmers' objectives to "values" that guide action or change. Values are defined as "permanent property of the individuals, less liable to change with time and circumstances" (Berbel and Rodriguez-Ocana, 1998). Values fall into four categories (Gasson (1973): 1) *Instrumental values*, e.g. maximizing income, saving income or expanding business. (2) *Social values,* e.g. belonging to a farming community, maintaining traditions, working with the family, respecting the village committee decisions, or doing what others do. (3) *Expressive values,* e.g. gaining self-respect, meeting a challenge. (4) *Intrinsic values,* e.g. enjoying working tasks, preferring healthy practices, valuing hard work, independence and freedom.

The game was played with 30 farmers sampled in four villages (10 in Leng, 12 in Lé, 5 in Xay and 3 in Dokham). The sampling maximized the diversity in farmers' resource endowment (crop area, number of head of cattle and family size) following the typology of Lestrelin and Kiewvongphachan (2017).

The game was composed of three sets of cards: "activity cards" representing farming activities, such as paddy rice, maize, cattle or off-farm job; "asset cards" representing assets, such as a motorbike or a sowing machine, and "bonus cards" representing extra resources, such as a labour workforce, land and money (Figure 2A). In a first step, the farmers were invited to discover and understand the cards. Then, each farmer was asked to tell the story of their farm and to explain the main choices they had had to make since they had become the head of the household. During the storytelling, the interviewer asked questions to elicit the reasons for the farmers' decisions and illustrated the changes by adding or removing activity and asset cards. The farmer was invited to validate or modify the deck to get accustomed to the use of the cards. The card combination at the end of the game represented the current farm situation (see example in Figure 2B). In a second phase, the farmer was invited to expose and explain their future five-year perspective with cards. Then, the interviewer substituted some activities by others to provoke the farmer's reaction. If the farmer rejected the proposed additional changes due to land, money or labour constraints, the interviewer displayed the corresponding bonus cards. Bonus cards were useful to avoid finishing the game with only a list of farmers' constraints rather than farmers' objectives. In a final step, the interviewer reformulated farmer choices and reactions until a list of objectives corresponding to the Gasson (1973) classification of values was found. The list was then shown to the farmer, who validated it and the interviewer asked the farmer to choose the three most important objectives. The results per objective were gathered for the four villages. The researchers then selected objectives as relevant criteria when more than 7% of the farmers selected the objective (i.e. two farmers out of the 30 interviewed).

Group game on important crop attributes

The aim of the group game was to identify farmers' important attributes for deciding which crop to grow on uplands. The game is called TAKIT and was created by Ornetsmüller *et al.* (2018). The game was played once per village in Lé, Leng and Xays, gathering 15-20 people in each village. Farmers were selected to cover farm system diversity, as in the card game. The facilitator introduced themself with this statement: "I am a trader and I have the best upland crop ever, what question would you like to ask me, in order to know if you would grow it or not?". Questions could only be answered with "yes" or "no"". The TAKIT game had four steps. The first step was a warm-up phase to explain game rules: two bottles were shown, one with water and the other with an unknown yellow liquid. Participants were asked to state the questions they would ask to know if they would drink the unknown yellow beverage. The questions were written, collected and sorted according to their similarity. Then the participants voted for three questions by giving a score from 3 (most important) to 1 (least important) and decided on whether to try the unknown beverage or not after having heard the answers. This first warm-up step was crucial to introduce the second step in which the yellow beverage was replaced by a fictional crop as it helped farmers to understand how to ask questions with yes/no answers. The second step was a real game focusing on the choice whether or not to grow a miraculous (fictional) crop with a presentation as exposed above. Farmers based their choice to grow the crop on the answers given by the facilitator to their questions. The third step was a ranking of the previous questions. The questions were presented on a board and participants chose their three most important questions by ranking them from most (score=3) to least (score=1) important. The fourth step was a discussion to identify farmers' criteria underlying their questions. For further details on the TAKIT methodology, the reader can refer to Ornetsmüller *et al.* (2018). Eventually, questions were grouped per village and an aggregated score was given to the questions by summing the scores given by farmers. The researchers selected questions with a score above one and aggregated them into a relevant list of criteria.

Soil fertility perception: Q-methodology

Q-methodology was not directly used to identify criteria, but rather as a complementary method to deepen our understanding of the farmer discourses used to select criteria during the group game and the individual card game. The group game revealed that farmers were concerned with soil fertility when deciding which crop to grow (See section 3.1.). We used a Q-methodology design (Brown, 1993) to study farmers' subjective perspectives when dealing with soil fertility by confronting them with a *Q-set*, i.e. a sample of 47 statements representing contrasting narratives on soil fertility (Table S1 and Figure S2 in Supplementary material). Statements were selected to maximize the diversity of opinions about soil fertility based on narratives the researchers heard during the three years of the study. We sampled 19 farmers in four villages (seven in Leng, five in Lé, four in Xay and three in Nadou). The sample maximized the diversity of soil types and degree of intensification in maize cropping systems. The Q-methodology was carried out individually with each farmer. Statements were written on cards in the Lao language and the interviewer first read all the cards to allow the farmer to ask questions for clarification. The farmers were first asked to divide the statements into three piles during the reading, i.e. statements they (i) agreed with, ii) disagreed with and iii) were neutral, doubtful or undecided about. The farmers were then asked to read the 47 cards and place them on the floor following a design that mimicked a normal distribution (Figure S2 in Supplementary material). The design had to be filled incrementally from left with cards they mostly disagreed with (score of -5) to right with cards they mostly agreed with (score of +5).

These 19 Q-sorts (i.e. farmers' statement classifications) were analysed with the centroid method and a varimax rotation (PQMethod software, see Van Exel and De Graaf (2005) and Iofrida *et al.* (2018) for a description of the method) was used to establish a typology of the farmers' opinions. For the most consensual statements, we calculated the percentage of farmers who ranked them at a position greater than or equal to +2 (most agreed statements) or lower than or equal to -2 (most disagreed statements).

2.4. Researcher perspective: agronomic diagnosis

Field monitoring network

To identify plot-level sustainability criteria, farmer-managed fields were monitored from 2016 to 2018 following the method of Doré *et al.* (1997). Contrasting plots in the farmers' maize fields were monitored. Firstly, participatory maps of low/high yielding areas, biophysically contrasting zones and crop management (Mascarenhas and Kumar, 1991) were drawn up through farmer focus groups, combined with field visits and a review of local knowledge on soils, climate, and crop management. We gathered groups of 10 farmers in three villages to draw up these participatory maps. The fields where then selected to ensure that they belonged to farmers from the three villages and covered the range of farm types, soil types and management diversity identified during participatory mapping. Plot size was set to 16 m² (to minimize within-plot heterogeneity, while keeping an area large enough to ensure reasonable measurement accuracy) and included 4 to 5 planting rows with a length of 3 to 5 m. We monitored 38 plots in 2016, 38 plots in 2017, and 35 plots in 2018 (n=111). For each cropping season, plots were located in 15 farm fields, i.e. more than one plot per field depending on within-field soil and crop management heterogeneity. Table 1 shows the monitored variables. Due to losses at harvest, 99 plots (out of 111) had observations for all the variables monitored: weed cover, pests, nutrient deficiency, yield components, crop management, soil analysis and weather data.

At the end of field monitoring, a soil typology was established with hierarchical clustering (R softwards, FactoMineR package, Lê *et al.* (2008)) based on a soil analysis, i.e. organic matter, nitrogen and phosphorus content, pH, sand, clay and silt contents and total cation exchange capacity. Cropping system types were clustered in a second step with a factorial analysis of mixed data (Escofier and Pagès, 2008), followed by hierarchical clustering. The variables used to cluster the cropping systems were soil type, slope, land preparation type, sowing tool and weed management.

Analysis of variability in agronomic and environmental performance at plot level

In order to identify the main factors driving plot agronomic and environmental performance, we calculated a range of variables derived from direct measurements, crop model simulations (Potential crop Yield Estimator (PYE), Affholder *et al.* (2013)) and farm surveys (Table 2).

The relative yield gap, water stress, nitrogen balance (N balance), nutrient deficiency, weed cover and pest damage score were considered as variables related to agronomic performance. The PYE model was used to simulate the potential (Y0) and water-limited (Yw) yields of the 111 monitored plots that informed the relative yield gap calculation. Y0 is the yield achieved when water and nutrient supplies exceed crop requirements and biotic stresses are absent. Factors determining potential yield are incoming solar radiation, temperature, atmospheric [CO_2], crop genetic characteristics and canopy light interception ability (van Ittersum and Rabbinge, 1997; van Ittersum *et al.*, 2013). Yw is similar to Y0, but with actual water supply that may limit crop growth (van Ittersum *et al.*, 2013). Table 2 gives more details on the calculation of the variables related to agronomic performance. The herbicide treatment index and erosion risks approximated with the length of the bare-soil period from ploughing to sowing, N balance and fertilizer doses, were considered as variables related to environmental performance (Table 2).

A first analysis looked at relating maize yield to the variables deemed important for agronomic performance (Table 2), i.e. single factor linear regressions of yield against water stress, potential N balance, and pest/weed scores. In a second analysis, two classification and regression tree (CART) models (Delmotte *et al.*, 2011; Tittonell *et al.*, 2008) were built (R software Rpart package, Terry Therneau and Beth Atkinson (2019)). The first CART aimed at identifying the main factors explaining yield variability. It was built on the total dataset (n=99) with the relative yield gap as the target variable (see Table 2 for calculation). Plausible yield-limiting and yield-reducing factors were set as explanatory variables: highest weed score, maize planting density, N balance and soil type. The second CART was performed with the main factor explaining yield gap variability (identified with the first CART) as the target variable. In the second CART, variables related to crop management were set as explanatory variables: i) weed management with 'false seed-bed', i.e. ploughing, letting weeds grow for one month and ploughing again (or herbicide spraying); ii) amount of work devoted to manual weeding; iii) sowing hole density at emergence; iv) number of days between last tillage and sowing and v) herbicide treatment index (see Table 2 for calculation).

Eventually, selection of the main drivers of variability in performance and impacts informed the creation of the sustainability criteria to be selected.

3. Results

3.1. Serious games and Q-methodology

Individual card game to determine famers' objectives

For respectively 83% and 80% of farmers, the objectives "be rice self-sufficient" and "have high incomes for savings" were the most important objectives (Table 3). The objectives "reduce work and effort" (77%), "have small regular incomes monthly for family expenditures" (77%), "diversify income" (63%) and "reduce cash-flow needed" (33%) were also frequently mentioned. A substantial share of farmers valued objectives related to sustainability: "transfer a viable farm to the next generation" (27%) and "avoid herbicides" (23%).

We determined five farm-level criteria by aggregating the objectives that mattered to farmers:

1) "Farm income - amount, consistency, cash-flow and risks", synthetized from the objectives "have high income for savings", "have small regular incomes monthly for family expenditures", "diversify income" and "reduce cash-flow needed"

2) “Diversity of activities”, synthetized from the objectives “diversify income” and “obtain incomes during the dry season”
3) “Workload peak and drudgery of work”, synthetized from the objectives “improve work productivity” and “reduce work and efforts”
4) “Rice and forage self-sufficiency”, related to the objectives “ be rice self-sufficient” and “be self-sufficient in animal feed”
5) “Farmer health”, related to the objective “Avoid herbicides” because it expressed farmers’ health concerns when spraying herbicide.

The objective “to be able to transfer a viable farm to the next generation” was related to overall farm sustainability (i.e. the performance for all the above-mentioned criteria) and was not included as a criterion itself. The objective “preserve a traditional activity” was not used as a criterion because (i) it was mentioned by only a small number of farmers (7%) and (ii) “traditional activity” would be hard to quantify. We did not consider the objective “perform activities that are easily manageable” as a specific criterion, but it was included in the criteria “farm income - amount, consistency, cash-flow and risks” and “workload peak, drudgery of work”. Indeed farmers during the group game revealed their fear of financial loss resulting from inadequate crop management and their reluctance to devote to a crop a large amount of work with too many interventions (see section below).

Group game on important crop attributes

Important attributes for choosing a crop differed between villages (Table 3). The two most important attributes for choosing a crop were i) suitability for village soil types and ii) improvement in soil fertility in Leng, i) storability of harvest and ii) ease of crop management in Lé, i) high yield and ii) ease of crop management in Xay. The game revealed the importance of soil fertility improvement for farmers, despite great variability between villages (score of 27 in Leng, 6 in Lé, while soil fertility was evoked through the ability of the new crop to be easily grown on village soil types in Xay). High crop yield was important in Xay (score: 30), whereas in Leng a good selling price and market channel availability were scored higher than yield. In the fourth step of the game, farmers explained that the "ease of crop management" attribute originated from (i) their fear of financial loss resulting from inadequate crop management and (ii) their reluctance to devote to a crop a large amount of work with too many interventions. The storability of harvest originated from the farmers' wish to control the selling period and prices.

We determined five plot-level criteria by aggregating the attributes that mattered to farmers:

1) "Economic performance - gross margin, return on investment, cash-flow and risk" (from the questions "Does it have a high yield?", "Does the crop have a good selling price?", "Does it have a good market (lot of buyers)?", "Is it expensive to grow it?", "Can we get a good benefit from it?", "Is the price stable?" and "Does it require a lot of fertilizer?")
2) Land productivity (from the question "Does it have a high yield?")
3) Susceptibility to pests (from the question "Is it a crop susceptible to pests?")
4) Work productivity and drudgery (from the questions "Is it easy to grow?" and "Does it require a lot of labour?")
5) Soil fertility (from the questions "Does it improve the soil?" and "Is it suitable for village soils?")

We did not use the question “Is it good for the environment?” because “good” was fuzzy and subjective, making it hard to identify a related sustainability criterion. We did not use the question “Does it require irrigation?” due to farmers’ misunderstanding, i.e. irrigation is available for lowlands, whereas the game was targeted at upland crop attributes.

The TAKIT game, although played to identify plot-level criteria, informed the identification of a farm-level criterion “farm autonomy”. Farm autonomy was related to the questions “Can we use it for our own consumption?” and “Is it storable”. Farmers were willing to cultivate upland crops to reduce food purchases (meaning lower autonomy) and farmers related storability to their ability to choose marketing timing and prices.

Q-methodology on soil fertility perception

Farmers agreed on five statements regarding soil fertility (Table 4): “The soil is fertile when it gives enough food to the plants to grow without mineral fertilizer addition”(84% of farmers), “Soils in flat land cleared from very old forest remain fertile even after 15 years of maize cultivation”(63% of farmers), “When there is enough rain, most of the soils of the village are still able to give good yields”(42% of farmers), “If the soil is deep, I know for sure that the soil is fertile”(47% of farmers), “Low crop yield in a good climatic year is an indicator of low fertility”(47% of farmers). They disagreed on three statements (Table 4): “Infertile maize fields have a lot of weeds” (63% of farmers), “Soils are more exhausted than before, but could give more yield today thanks to mineral fertilizer, a good variety and herbicide” (42% of farmers), “Low maize density is the main cause of low yield compared with low soil fertility” (42% of farmers).

We identified three contrasting opinions about soil fertility. "*Progressive-minded"* farmers (opinion 1-O1, Table 4) agreed that (i) "Legumes can improve soil fertility" and (ii) "If the soil has a black colour, it is a fertile soil, and if the soil is red or yellow it is an infertile soil", and (iii) "Soil fertility has decreased because of ploughing every year". They disagreed with "Farming practices today will impact the future generations, but there is no other alternative". Farmers with opinion 1 were slightly more concerned by long-term issues than the others, since the statement "I want to preserve the fertility of my soil for the future farm of my children" was one of their five most agreed statements (table 4). Those farmers also disagreed with "It is not worth it to invest time and money in soil fertility". By contrast, "*Income-minded"* farmers (opinion 2-O2, Table 4) attached more importance to soil structure after ploughing and disagreed strongly with the statement "Farmers have a duty to conserve soil for the next generation, whatever the impact on today's profits". Soil fertility was not only equivalent to high yields for them, they disagreed strongly with "No matter the colour and the structure of the soil, a fertile soil has a high yield without adding mineral fertilizer". *"No-alternative"* farmers (opinion 3-O3, Table 4) agreed that (i) "Farming practices today will impact the future generations, but there is no other alternative", (ii) "A fertile soil is mellow and has a good structure after ploughing". They also believe that "Soil erosion leads to a decline in fertility because the most fertile layer disappears" (most agreed statement). They disagreed with (i) "A fertile soil is a soil where it is easy to obtain a satisfactory plant density at emergence with a seed drill", (ii) "The use of herbicides makes the soil less fertile". The identification of "*progressive-minded*" farmers showed that soil fertility criteria were not necessarily related to short-term income maximization in farmer's minds. Interestingly, the Q-methodology showed that a group of farmers expressed a complex perception of soil fertility beyond a mere concern for high yields and immediate profits, i.e. they were willing to preserve it for future generations. Even "*income-minded*" farmers did not relate soil fertility to high yields alone.

The outcomes of the Q-methodology led the researchers to keep the soil fertility criteria identified with the TAKIT game as an independent criterion not necessarily related to the economic performance and land productivity criteria. The Q-methodology allowed the researchers to add "soil erosion" to the list of plot-level criteria previously established after the group game.

Overall, the serious games showed that socio-economic dimensions generally prevailed over environmental long-term perspectives in farmers' objectives. Nevertheless, some farmers valued some long-term issues, such as their capacity to transfer a viable farm to their children and to maintain soil fertility for the next generation. The games highlighted the prevalence of the socio-economic dimension in farmers' objectives, and the crucial role of maize performance for farmers.

3.2. Agronomic diagnosis

Constraints and sustainability issues possibly occurring in maize areas, as found during a review of local knowledge and used to set up field monitoring, can be found in supplementary material, Table S2. Farmers distinguished three soil types during participatory mapping: red-sandy soils (low yields), loamy-clayey soils (medium to high yields) and yellow sandy soils (medium to high yields). Farmers identified three types of crop management: high-input intensified systems (mechanical sowing, harrowing after ploughing, fertilizer and herbicide use), medium-input intensified systems (mechanical sowing, no harrowing, herbicide or fertilizer) and low-input intensified systems (hand sowing, no harrowing and herbicide). The participatory mapping combined with the review of local knowledge and field visits helped identify the following criteria to select the plots to monitor: farmer-reported yields, slope, level of agricultural intensification, soil type and soil quality as visually appraised by the farmer.

After monitoring, five contrasting types of cropping systems were identified (Table 5) depending on slope, type of sowing (mechanical or manual), amount of herbicide use, and time between soil preparation and sowing. Clayey-loamy soils, the dominant soil type in the monitored plots, had, on average, an organic nitrogen content of 0.096%, a soil organic matter content of 2.44%, a total cationic exchange capacity of 9.7 me/100g and a pH of 6.01 (see Figure S3 for detailed results of soil analysis and soil type). Herbicide application varied greatly (Table 5). The herbicide treatment index for cropping system 3 (moderate slopes, hand or mechanical sowing on clayey-loamy soils, short period of bare soil before sowing) was more than three times the recommended dose, whereas it was equal to 0 for cropping system 4 (flat land, mechanical sowing on clayey-loamy soils, medium period of bare soil). Fertilization rates were low with 20 kg of N ha^{-1}, on average, in fertilized plots and never exceeded 40 kg N ha^{-1}. The potential N balance was below -10 kg ha^{-1} for 90% of the plots (Table 5). The potential N balance was lowest on the sandy soils of cropping system 2 (flat land, mechanical sowing on low-fertility sandy soils, medium period of bare soil). Risks of erosion were either due to slopes or due to a long period between ploughing and sowing. The number of days between ploughing and sowing varied from 3 to 108 and averaged 29 days. Cropping systems 3 and 5 had contrasting erosion risks, the former having a short bare soil period before crop installation and the latter a long period, due to a false seed-bed practice to reduce weed pressure.

The average potential (Y0) and water limited (Yw) yields were 6.2 t ha^{-1} and 6.0 t ha^{-1}, respectively, for the 111 plots simulated with the crop model. The limited difference between Y0 and YW indicated a low impact of water stress on yields in the monitored plots. This was not surprising because northern Laos has a humid sub-tropical climate**.** The Kham basin had a total annual rainfall of 854, 875 and 1569 mm in 2016, 2017 and 2018, respectively. The observed maize yields (Ya) in the monitored plots were markedly below Yw and highly variable. Ya ranged from 0.7 t ha^{-1} to 5.3 t ha^{-1} and averaged 2.8 t ha^{-1} (Table 6). In all, 25% of the plots had a yield below 1.9 t ha^{-1}. The relative yield gap ranged from 8% to 89%, and 25% of the plots had a very high relative yield gap above 68%.

Field monitoring revealed the prevalence of weed infestation to explain yield variability, itself mainly explained by sowing hole density. Yields were correlated to “Highest weed score” (R^2=0.19, P<0.001) and potential N balance (R^2=0.08, P<0.005). Weed infestation was significantly correlated with sowing hole density (Figure 3). When dealing with crop competition with weeds in our context, sowing hole density mattered more than plant density. Indeed farmers dropped two seeds into each hole by hand, while the seed drill dropped one seed per hole. Therefore, for the same sowing hole density, manual sowing led to a plant density double that achieved with the seed drill, but with the same space (and light for weeds) between holes. Sowing hole density varied greatly from 1.1 to 8.1 sowing holes m^{-2}. A higher sowing hole density was achieved with mechanical sowing compared with manual sowing (Figure 3B), but only 4% of farmers achieved the optimum sowing hole density of 7.1 plant m^{-2} enabled by the seed drill. Pest stress was not identified as an explanatory variable of yield variation, as only 6% of the plots experienced it.

In CART, “Highest weed score” was the main variable explaining relative yield gap variability (Figure 4A). The plot relative yield gap (Yr) was categorized in eight groups (R^2=0.37) according to criteria of decreasing importance: highest weed score, potential N balance, and plant density. The average relative yield gap was 59% for plots with “Highest weed scores” above 4.8, and 45% for plots below 4.8. For plots with a high weed score, Yr was 69% when the potential N balance was below -78 kgN ha^{-1} and 54% when the N balance was above that threshold. Similar interpretations could be derived by reading the other branches of the tree. Weed infestation variability was first explained by sowing hole density (Figure 4B), followed by herbicide doses and number of days between the last soil tillage and sowing (R^2=0.47).

The key outcomes revealed by the agronomic diagnosis were: i) high yield variability, high yield gaps and a high risk of failure, ii) low sowing density leading to: high weed pressure, low yields, low resource use efficiency, a high workload for weeding and a low return on cash investment, iii) herbicide overuse and leaching risks due to weed infestation, iv) erosion risks due to a long bare-soil period between ploughing and sowing, v) risks of fertility loss because of a negative N balance in maize plots. The latter can be explained by the fact that maize fields were used for cattle roaming in the dry season and the manure collected at night was exclusively used for lowland rice.

The outcomes of the agronomic diagnosis informed the determination of the following plot-level criteria: 1) Land productivity: yield variability and risk of failure, 2) Soil erosion, 3)

Susceptibility to weeds, 4) Resource use efficiency, 5) Work productivity and drudgery, 6) Herbicide risks, 7) Economic performance. At farm level the agronomic diagnosis informed the determination of the criterion “Fertility transfer”.

Eventually, we added criterion sensitivity to climate variability, because environmental impacts (e.g. erosion, herbicide leaching) were also related to rainfall events. We added susceptibility to pests and biodiversity criteria, because the agronomic diagnosis revealed that maize fields were managed in a sole stand mono-cropping system, reinforcing weed infestation over the years.

3.3. Integration of knowledge to select the final set of criteria

Plot-level sustainability criteria

Figure 5 shows the final set of criteria resulting from an integration of farmer and scientist perspectives. Every criterion identified can be quantified with indicators. On the left-hand side of the figure, the final plot-level criteria are displayed combining the serious games and Q-methodology results with the agronomic diagnosis: economic performance, land productivity, susceptibility to pests, weeds, diseases and climate variability, work productivity and drudgery, soil erosion, herbicide risks, biodiversity, soil fertility, and resource use efficiency. To establish this final list, the criteria originating from the serious games were grouped with those from the agronomic diagnosis, e.g. “economic performance” includes gross margin (derived from the TAKIT game), return on investment (derived from the agronomic diagnosis and the TAKIT game) and cash flow (derived from the card game and the TAKIT game).

Farm-level sustainability criteria

On the right-hand side of Figure 5, the final farm-level criteria are displayed combining the serious games and Q-methodology results with the agronomic diagnosis: farm income (amount, consistency, risk and cash flow), diversity of activities (risks), workload peak, drudgery of work, farmer autonomy, rice/forage self-sufficiency, fertility transfer, and farmer's health risks due to herbicides. To establish this final list, the criteria originating from the serious games were grouped with those from the agronomic diagnosis, e.g. farmer health includes herbicide overuse (derived from agronomic diagnosis) and farmers' concerns when spraying herbicide (derived from the card game).

4. Discussion

4.1. Strengths and pitfalls of each part of the method

Long-term perspective with serious games and Q-methodology

From the farmers' perspective, socio-economic objectives were predominant and food security was crucial. This was foreseen, given the high poverty incidence among farmers in the study region (Coulombe *et al.*, 2016). However, long-term concerns were not completely ignored by the farmers. The importance given to soil fertility in the serious games may, however, have been due to a desirability bias, i.e. the tendency of farmers to answer strategically to be favourably perceived by the interviewer (Lusk and Norwood, 2010; Wheeler *et al.*, 2019). We tried to minimize this bias by presenting ourselves as researchers from an international agricultural research centre and did not put any particular emphasis on technologies related to soil fertility improvement. The importance given to soil fertility improvement may also have expressed the farmers' desire to achieve high yields rather than long-term productivity. The results of the Q-methodology, however, weakened such a hypothesis, because some of the farmers were concerned by soil fertility degradation and wanted to preserve it for the next generation. The farmers' long-term objective to transfer a viable farm to the next generation, identified during the card game, suggests that after 20 years of maize monoculture, farmers were concerned about the sustainability of maize-based systems. Unravelling the factors driving maize cropping system sustainability was crucial.

Drivers of cropping systems sustainability with the agronomic diagnosis

Maize cropping system performance varied widely, but single factors (weed and pest competition, N balance, and water stress) explained only 19% (r^2=0.19) of the variations (at best) and CART 37% (at best). Substantial remaining unexplained variation is, however, a common feature of on-farm trials in a smallholder context (Baudron *et al.*, 2012; Falconnier *et al.*, 2016; Naudin *et al.*, 2010). An unexpected result of field monitoring compared to the local discourse (see Table S2 in Supplementary material) was the predominance of weed pressure over soil fertility to explain yield variability. Soil fertility remains an issue for the long-term sustainability of cropping systems, given the negative farm-level nutrient balance found in the region (Epper *et al.*, 2020), but weed pressure and plant (and sowing hole) density drive maize cropping system sustainability. With mechanical sowing, the low sowing density was probably due to a malfunctioning of the seed drill. The seed drill opens by friction with the ground surface. Sub-optimum soil moisture conditions after tillage created large soil clods and could have prevented the seed driller from operating properly. Sub-optimum soil conditions can be due to: i) limited access to ploughing services, compromising the timeliness of the operations and ii) a short time window for rice and maize establishment, with farmers focusing on rice cultivation, hurrying maize sowing to spare time for paddy rice preparation. Beyond yield variability, poor crop establishment also favoured detrimental environmental impacts, such as herbicide overuse to control weeds, and potentially risks of erosion and nitrogen leaching.

Direct measurements are more time-consuming and cost-intensive than rapid farmer surveys and cannot be implemented easily to reach a large number of farmers. Agronomic diagnosis is a methodology easily applied by an experienced agronomist trained to implement it quickly over one or two cropping seasons. However, in line with our objective to publish a scientific paper, plot monitoring was carried out over three cropping seasons, i.e. a long period for a prior analysis to guide the design and implementation of sustainable options for farmers. Field monitoring was necessary to dismiss preconceived ideas (i.e. low yields are due to poor soil fertility) and to explain the drivers of sustainability (see section 4.2). Moreover, the quantitative data collected on maize cropping systems were crucial for multi-criteria assessment at farm level and were the basis for the quantification of indicators at that level.

4.2. Added value of our approach combining two perspectives

We identified some pitfalls of existing broad-based methods for our case study, namely i) a lack of integration of multiple perspectives (farmers, experts and scientists) to identify the sustainability issues at stake, ii) an insufficient consideration of the local context for criteria selection, and iii) a lack of transparency regarding the scientific logical reasoning that led to that selection (Niemeijer and de Groot, 2008).

Integration of multiple perspectives

The identified sustainability criteria determine the results of the assessment. In our case study, integrating knowledge from scientists and farmers with a mixed-method approach made it possible to embrace the plurality of views on sustainability. Scientific analyses at plot level were useful for explaining and understanding the biophysical processes at stake in sustainability issues. Qualitative data from the serious games and Q-methodology at plot and farm levels were useful for understanding farmers' perceptions, objectives and concerns. The two types of knowledge taken separately would have been incomplete for determining relevant criteria, because: i) quantitative insights obtained in field monitoring lacked farm-scale contextualization integrating farmers' decisions and constraints; ii) qualitative insights gained through the serious games were village-specific and difficult to generalize. Field monitoring therefore helped in understanding certain outputs of the serious games results.

Combining the two perspectives, we showed that farmers' willingness to maintain soil fertility contrasted with current soil management associated with negative N balances and risks of erosion. Field monitoring showed that, in the current state of maize cropping systems, it was probably not profitable for farmers to invest time and money for fertility management in fields with poor crop performance, partly due to poor crop establishment and the resulting weed pressure. Our study revealed discrepancies between farmers' perspectives and agronomic facts: farmers generally disagreed with the statement "Low maize density is the main cause of low yield compared with low soil fertility" (See section 3.1), while field monitoring revealed the crucial role of a low plant density and subsequent weed infestation in explaining low yields. An interesting result of the agronomic diagnosis to complement farmers' perspective was the three criteria not explicitly mentioned by farmers in the serious games and Q-methodology: erosion risks due to bare soil, low sowing density leading to risks of high weed pressure, herbicide overuse and leaching risks due to weed pressure. Van Asten *et al.* (2009) showed that farmers struggle to identify yield-constraining factors when constraints are uniform in time and space. Co-learning cycles engaging farmers and researchers, with quantitative field monitoring and feedback sessions, can contribute to the convergence of farmers' and scientists' views (Falconnier et al., 2017, Hanna *et al.*, 2014).

The TAKIT game pinpointed a village effect on farmers' preoccupations (see section 3.1), which was elucidated thanks to the field monitoring. In all, 80% of monitored fields in Leng belonged to cropping systems 4 and 5 (higher fertilizer rates), while 65% of monitored fields in Xay belonged to cropping system 1 (steep slopes, hand sowing, no fertilizer on low-fertility soils) (see section 3.2). Farmers in the village of Leng obtained slightly higher yields (3.12 t/ha) than their counterparts in Xay (2.54 t/ha). Consequently, farmers in Leng gave more importance to a good selling price and market channels than the farmers in Xay.

Consideration of the local context to select criteria

We compared our final set of criteria with some other sets used in existing generic methods (Gomiero and Giampietro, 2001; Dalsgaard and Oficial, 1997; Liebig *et al.*, 2001; Hassall et al, 2005; Waney *et al.*, 2014; Castoldi and Bechini, 2010; Meul *et al.*, 2008). Some of our criteria were similar (e.g. erosion, pesticide use, productivity), but some issues would not have been well covered with a generic framework. For example, at plot level, a pre-defined set of criteria would have missed the relevance of the criteria "resource use efficiency" or "crop sensitivity to weeds" as identified with field monitoring. A focus on soil fertility, as emphasized in most existing methods, would certainly have hidden the importance of other yield-constraining factors, such as weed infestation linked to sowing density and appropriate crop establishment.

Transparency regarding scientific logical reasoning

Scientific objectivity did not lie in the fact that science brought our understanding closer to "pure knowledge" devoid of subjectivity (Alrøe and Kristensen, 2002), but rather lay in the transparency of the methodology used and the assumptions made. In our case study, transparency was reached because we answered a particular question in view of a specific objective, and explained the choices made for abstraction of the system assessed, and the consequences of the simplified representation for the reality of the conclusions.

Our approach highlighted the role of science and the importance of quantitative data for understanding sustainability, a value-based concept. Any scientific assessment has assumptions, values or preferred fields of interest (Sala *et al.*, 2015). Indeed, 20th century epistemologists dispelled the idea that scientists are devoid of value, independent and detached observers of the world (Alrøe and Kristensen, 2002; Chalmers and Biezunski, 1987). The aim of in-field monitoring was to go beyond facts that were generally accepted by the scientific community and farmers. Our experimental design swept aside preconceived ideas of experts on sustainability, to start afresh in our selection of criteria.

In developing countries, where farms have shifted from subsistence to market-oriented systems, sustainability evaluations are challenging. Quantitative data are scarce, or lack reliability, because they are often based on farmer-reporting (*e.g*. Lobell et al. (2019)), which makes them inappropriate for understanding drivers of sustainability. Our approach combined credible agronomic information and farmers' perspectives with logical reasoning.

5. Conclusion

Over a period of three years we applied a multi-level and multi-method approach that combined farmers' and researchers' perceptions of sustainability in northern Laos. This study contributes to the need to integrate farmers' and scientists' views and opinions on sustainability, as each vision is incomplete without the other. Several complementary analyses, from plot to farm level, helped to identify a set of locally relevant sustainability criteria. These criteria can be used to compare different farming systems in relation to their sustainability. The list of criteria identified in this study is currently being used to explore with ex-ante farm modelling pathways, to improve the sustainability of maize-based systems in the region.

We found that, beyond the standard socio-economic criteria expected for poor farmers, farmers also valued other long-term sustainability criteria (e.g. transfer a viable farm, impact of agricultural practises on human health and soil fertility). At plot level, field monitoring showed that the ability of farmers to ensure good crop establishment was a strong determinant of maize system sustainability. Today in the Kham basin, while it is true that maize-based cropping systems are facing serious sustainability issues, our diagnosis revealed that it is mainly inadequate crop management during crop installation that leads to low resource use efficiency and unsustainable trajectories.

The approach presented here is useful for understanding farming system sustainability based on local priorities, as perceived by farmers and scientists. The approach can assist the design of multi-criteria assessments of alternatives to the current maize-based cropping systems and contribute to informing priority-setting for institutional development and agricultural policies in the region.

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Table 1: List of variables monitored in the field monitoring network

	Unit	Timing or frequency of measurement	Source of data
Weed cover, pests, nutrient deficiency			
Weed cover score	Score from 1 to 9	Every month	Field observation
Disease and pest severity score	Score from 1 to 5		
Nutrient deficiency score	Score from 1 to 5		
Yield components			
Plant and sowing hole density	Plants (and holes) m^{-2}	At emergence and harvest	Field measurement
Number cobs / plant	Cobs plant^{-1}	At harvest	Field measurement
Yield	t ha^{-1}	At harvest	Field measurement
Total aboveground biomass	t ha^{-1}	At harvest	Field measurement
Weight of a thousand kernels	g	At harvest	Field measurement
Phenological stages	Date	At emergence and flowering	Field observation
Maximum Leaf area index	m² m^{-2}	At flowering	Field measurement
Crop management			
Soil management (type and date)	Date	After each field operation	Farm surveys
Soil management (labour requirement)	Man-days		
Herbicide applications (type of product and date)	Date		
Herbicide applications (amount)	kg or litres		
Fertilizer applications (type of product and date)	Date		
Fertilizer applications (amount)	kg		
Manual weeding (date)	Date		
Manual weeding (labour requirement)	Man-days		
Soil analysis			
Available water capacity	mm to maximum rooting depth	Once in 2017 in August	Lab analysis
Textural and chemical analysis		Once in 2017 before growing season	
- Cationic exchange capacity	me/100g		
- Soil texture (sand, silt, clay)	%		
- Organic matter	%		
- Total nitrogen	‰		
- Total phosphorus	‰		
- pH	-		
Weather data			
Rain	mm	Every hour during growing season	Campbell station + Tinytag
Temperature	°C		
Humidity	%		
Global radiation	kW m^{-2}		
Wind	m s^{-1}		

Table 2: Variables used to explain plot-level agronomic and environmental performance (with units in brackets). *Yw*: potential water-limited yield, *Ya*: observed actual yield, *LAIw*: Leaf Area Index, water limited, *LAI0*: potential Leaf Area Index, Y0: potential yield, *Nmin*: nitrogen mineralized from total soil organic nitrogen (kg ha^{-1}), *Nfert*: amount of mineral nitrogen applied (kg ha^{-1}), *Nuptake*: nitrogen uptake from soil by maize (kg ha-^{1}), *NtotSoil*: total soil organic nitrogen (kg ha^{-1})

	Calculation	Type of indicator computation
Agronomic performance		
Relative yield gap (%)	(Yw -Ya)/Yw * 100	Direct measurement; PYE model simulation
Water stress (-)	LAIw/LAI0 Yw/Y0	PYE model simulation
Potential nitrogen balance *(kg ha^{-1})* *Quantity of nitrogen potentially left in the soil for maize yielding at water-limited potential*	Nmin + Nfert − Nuptake Where -Nmin=(30/20)*68*[NtotSoil] if pH>7 and -Nmin= (30/20)*0.25*([pH]-3)*68*[NtotSoil] if pH<7 (QUEFTS model, Sattari et al. 2014) -Nuptake= Yw*21 *(21 is N (kg) taken up per ton of maize grain at 12% humidity Standford (1973), assumed for a maize yielding at 6.278 tons/ha)*	Direct measurement; PYE model simulation; QUEFTS equation outputs
Nutrient deficiency (number)	Score based on observation of leaf colour, 1 to 5	Observation
Weed cover score (number)	-Weed score 30 days after sowing, 1 to 9 -Highest weed score (from 30 days after sowing to harvest), 1 to 9	Observation
Pest damage severity score (number)	Score, 1 to 5	Observation
Environmental performance		
Herbicide treatment index (HTI) (number of recommended doses)	HTI= (applied dose)/(recommended dose* area of the field)	Farmer survey
Erosion risk (number)	Number of days between ploughing and sowing	Farmer survey
Potential nitrogen balance (kg ha^{-1})	See above	See above
Mineral fertilizer use (Kg.ha-1)	Doses	Farmer survey

Table 3: Farmers' objectives and important crop attributes resulting from card and group games carried out with farmers in three villages of northern Laos. For the group game the final score was obtained by summing the scores given by farmers in a given village (see section 2.2).

Village	**Farmers' objectives** (five-year perspective) **(card game)**	% farmers
Lé, leng, Xay and Dokham	Be self-sufficient in rice	83%
	Have high incomes for savings	80%
	Reduce work and efforts	77%
	Have small regular incomes monthly for family expenditures	77%
	Diversify income	63%
	Reduce cash-flow needed	33%
	Transfer a viable farm to the next generation	27%
	Avoid herbicides	23%
	Improve work productivity	17%
	Obtain income during the dry season	13%
	Perform activities that are easily manageable	7%
	Be self-sufficient in animal feed	7%
	Preserve a traditional activity	7%
	Have free time for family	3%
	Protect the environment	3%
	Have a healthy lifestyle	3%
	Reduce the work needed on uplands to focus on paddy rice	3%
	Group lands together around the farm	3%
	Be self-sufficient in clothes	3%
	Crop attributes important for farmers (Takit group game) = answer to the question "I am a trader and I have the best upland crop ever, what question would you like to ask me, in order to know if you would decide to grow it or not?"	Score
Leng	Is it suitable for village soils?	**28**
	Does it improve the soil?	**27**
	Does the crop have a good selling price?	**8**
	Does it have a good market (lot of buyers)?	**5**
	Does it have a high yield?	**4**
	Is it expensive to grow it?	**2**
	Can the project help us for the implementation?	0*
	Is it a crop susceptible to pests?	0*
Lé	Is it storable?	**20**
	Is it easy to grow?	**20**
	Does it require a lot of labour?	**7**
	Does it have a good market (lot of buyers)?	**6**
	Does it improve the soil?	**6**
	Does the crop have a good selling price?	**5**
	Is it suitable for village soils?	**3**
	Can we use it for our own consumption?	**3**
	Does it require a lot of fertilizer?	**2**
	Does it have a good yield?	**2**
	Can we get a good benefit from it?	**1**

	Does it require irrigation?	**1**
	Is it good for the environment?	**1**
	Is the price stable?	**1**
	Can we grow it together with another crop?	0
	Is it a dry-season crop?	0
	Is it a crop susceptible to pests?	0
	Is it a rainy season crop?	0
Xay	Does it have a good yield?	**30**
	Is it easy to grow?	**15**
	Do technicians recommend us to grow it?	**12**
	Does the crop have a good selling price?	**10**
	Is it suitable for village soils?	**7**
	Does it have any contracts with a company to grow it?	**6**
	Is it a healthy crop?	**5**
	Does it have a good market (lot of buyers)?	**3**

*the question was mentioned in the preliminary steps but no farmers finally ranked it as important.

Table 4: Farmers' soil fertility perception based on a sample of statements representing contrasting narratives on soil fertility. The three types of opinions (O1, O2 and O3) were identified with the centroid method and a varimax rotation (see section 2.2). Only the statements that created the most distinguishing classification among the different opinions are shown. The full list of statements can be found in Table S1.

	Average score			
	O1	O2	O3	
Statements for which most farmers disagreed (no statistical difference at 95% between opinions)				**%farmers score<-1**
Infertile maize fields have a lot of weeds	-3	-5	-3	63%
Soils are more exhausted than before, but could give more yield today thanks to mineral fertilizer, a good variety and herbicide	-2	-1	-1	42%
Low maize density is the main cause of low yield compared with low soil fertility	-1	-1	-1	42%
Statements for which most farmers agreed (no statistical difference at 95% between opinions)				**%farmers score>1**
The soil is fertile when it gives enough food to the plants to grow without mineral fertilizer addition	5	4	5	84%
Soils in flat land cleared from very old forest remain fertile even after 15 years of maize cultivation	3	4	4	63%
When there is enough rain, most of the soils of the village are still able to give good yields	1	3	2	42%
If the soil is deep, I know for sure that the soil is fertile	3	1	1	47%
Low crop yield in a good climatic year is an indicator of low fertility	2	2	1	47%
Statements describing O1				
- **For which there is a statistical difference with O2 and O3**				
Legume crops can improve soil fertility	**5**	0	1	
If the soil has a black colour, it is a fertile soil, and if the soil is red or yellow it is an infertile soil	**4**	-2	-3	
Soil fertility has decreased because of ploughing every year	**1**	0	0	
A fertile soil is mellow and has a good structure after ploughing	**0**	5	3	
The use of herbicides makes the soil less fertile	**0**	-2	-4	
Farming practices today will impact the future generations, but there is no other alternative	**-2**	0	4	
- **Most agreed statements**				
Legume crops can improve soil fertility	**5**	0	1	
The soil is fertile when it gives enough food to the plants to grow without mineral fertilizer addition	**5**	4	5	
If the soil is black, it is a fertile soil and if the soil is red or yellow it is an infertile soil	**4**	-2	-3	
I want to preserve the fertility of my soil for the future farm of my children	**4**	1	2	
- **Most disagreed statements**				
Maize grows well even if the soil is not fertile, unlike other upland crops	**-5**	-2	-4	
Mineral fertilizer makes the soil stronger	**-5**	0	-4	
It is not worth it to invest time and money in soil fertility	**-4**	-2	-2	
I prefer to have a high income today, because I need money immediately, even if I do not preserve soil fertility	**-4**	-3	-2	
Statements describing O2				
- **For which there is a statistical difference with O1 and O3**				
A fertile soil is mellow and has a good structure after ploughing	0	**5**	3	

After ploughing, a fertile soil has clods that easily burst with rainfall	-1	**5**	-1
Mineral fertilizer makes the soil stronger	-5	**0**	-4
The use of herbicides makes the soil less fertile	0	**-2**	-4
Farmers have a duty to conserve soil for the next generation, whatever the impact on today's profits	2	**-4**	2
- **Most agreed statements**			
A fertile soil is mellow and has a good structure after ploughing	0	**5**	3
After ploughing, a fertile soil has clods that easily burst with rainfall	-1	**5**	-1
Soils in flat land cleared from very old forest remain fertile even after 15 years of maize cultivation	3	**4**	4
Fallow was used before maize to help the soil rest and soil fertility increase	3	**4**	3
- **Most disagreed statements**			
Infertile maize fields have a lot of weeds	-3	**-5**	-3
No matter the colour and the structure of the soil, a fertile soil has high yield without adding mineral fertilizer	-1	**-5**	-1
Some soils were infertile before maize, others became infertile due to maize cultivation	-1	**-4**	-2
Farmers have a duty to conserve soil for the next generation, whatever the impact on today's profits	2	**-4**	2
Statements describing O3			
- **For which there is a statistical difference with O1 and O2**			
Farming practices today will impact the future generations, but there is no other alternative	-2	0	**4**
A fertile soil is mellow and has a good structure after ploughing	0	5	**3**
A fertile soil is a soil where it is easy to obtain a satisfactory plant density at emergence even if rainfall events are scarce	2	3	**-2**
A fertile soil is a soil where it is easy to obtain a satisfactory plant density at emergence with a seed drill	0	3	**-3**
The use of herbicides makes the soil less fertile	0	-2	**-4**
- **Most agreed statements**			
The soil is fertile when it gives enough food to the plants to grow without mineral fertilizer addition	5	4	**5**
Soil erosion leads to a decline in fertility because the most fertile layer disappears	2	3	**5**
Soils in flat land cleared from very old forest remain fertile even after 15 years of maize cultivation	3	4	**4**
It is important to prevent soil fertility loss even if we have to work more by doing so	1	-1	**4**
- **Most disagreed statements**			
Fertilizer and cow manure are the same for fertility improvement	-3	-2	**-5**
Maintaining soil fertility is not labour-intensive	-4	-3	**-5**

Table 5: Types of maize cropping system according to crop management and soil type. Environmental performances per type are displayed in the second part of the table. “low”, “medium”, “high” correspond to equal distribution of quantitative observations in three qualitative classes. See Table 1 for details on environmental indicator computation.

Cropping system	**1**	**2**	**3**	**4**	**5**
Crop management and soil type					
Number of plots	23	11	13	27	29
Slope	Steep	Gentle	Moderate	Gentle	Gentle
Type of sowing	Hand	Mechanical	Hand or mechanical	Mechanical	Mechanical
Harrowing	No	No	Yes or no	Yes	Yes
Bare soils before sowing	Low	Medium	Low	Medium	High
Soil type	Clayey-sandy soils; mostly low fertility	Sandy soils; low fertility	Clayey-loamy soils; medium to good fertility	Clayey-loamy soils; medium to good fertility	Clayey-loamy soils; medium to good fertility
Weed management	Hand or/and herbicide	No hand weeding High doses of herbicide used	High doses of herbicide used	Mostly hand weeding Low doses of herbicide used	Hand weeding rare High doses of herbicide used False seed-bed
Indicators of environmental performance					
Mineral fertilizer use (kgN ha^{-1})	8	7	3	14	16
N balance (kg ha^{-1})	-80	-97	-13	-59	-59
Herbicide treatment index (HTI)	1.7	1.8	3.2	0	2.4
Erosion risk (days)	21	28	12.5	25	46.5

Table 6: Variability in measured maize yield, relative yield gap, plant density and sowing hole density in the field monitoring network (n=99)

	Yield ($t\ ha^{-1}$)	Relative Yield Gap, water limited (%)	Plant density at harvest ($plants\ m^{-2}$)	Sowing hole density ($holes\ m^{-2}$)
Min.	0.7	8	1.9	1.1
1st Quartile	1.9	42	3.5	3.1
Median	2.8	54	4.3	3.9
Mean	2.8	54	4.5	4.1
3rd Quartile	3.6	68	5.3	4.9
Max.	5.3	89	7.5	8.1

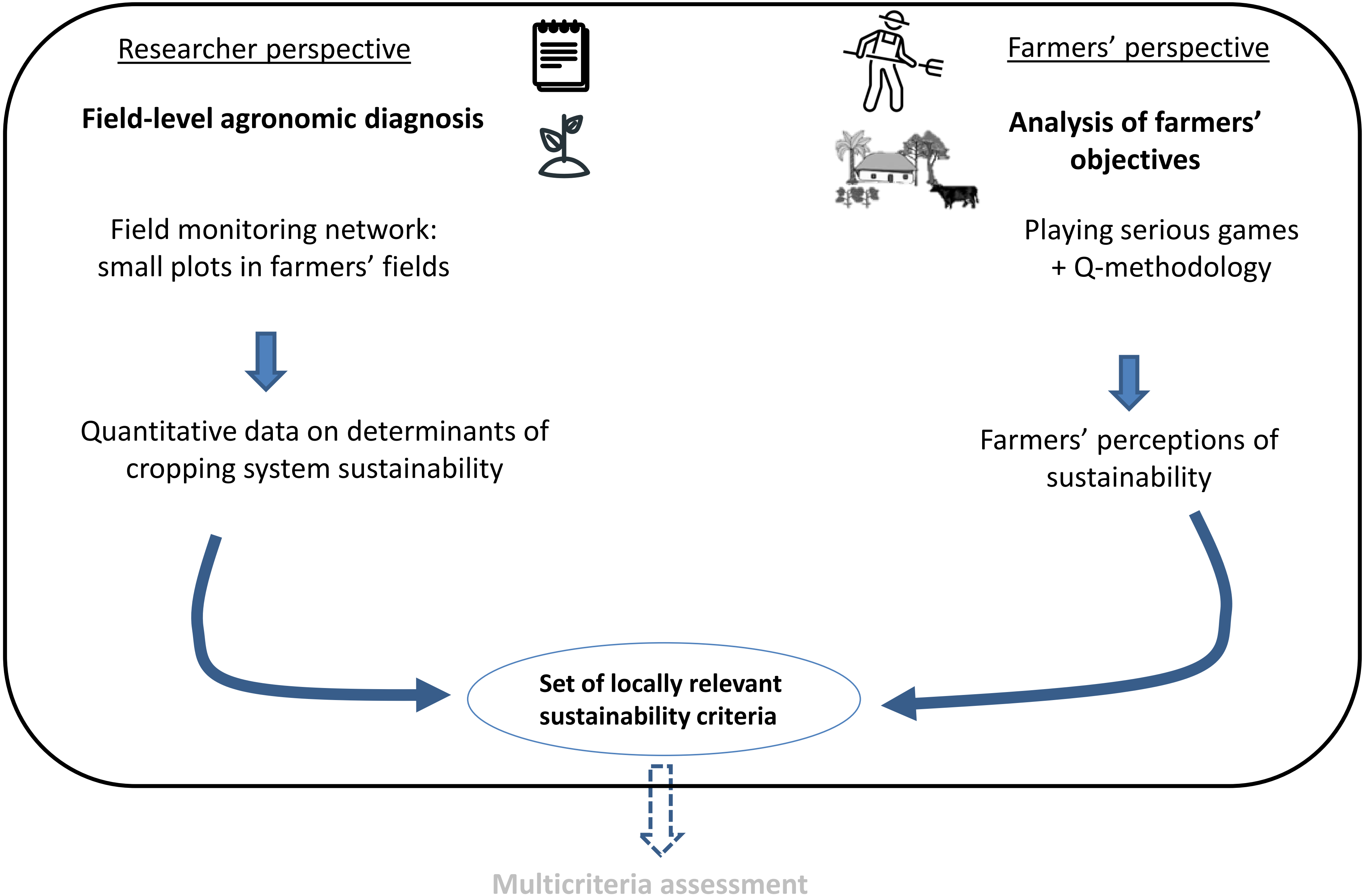

Figure 1: General approach of this study to identify complementary perspectives and determine a set of locally relevant sustainability criteria.

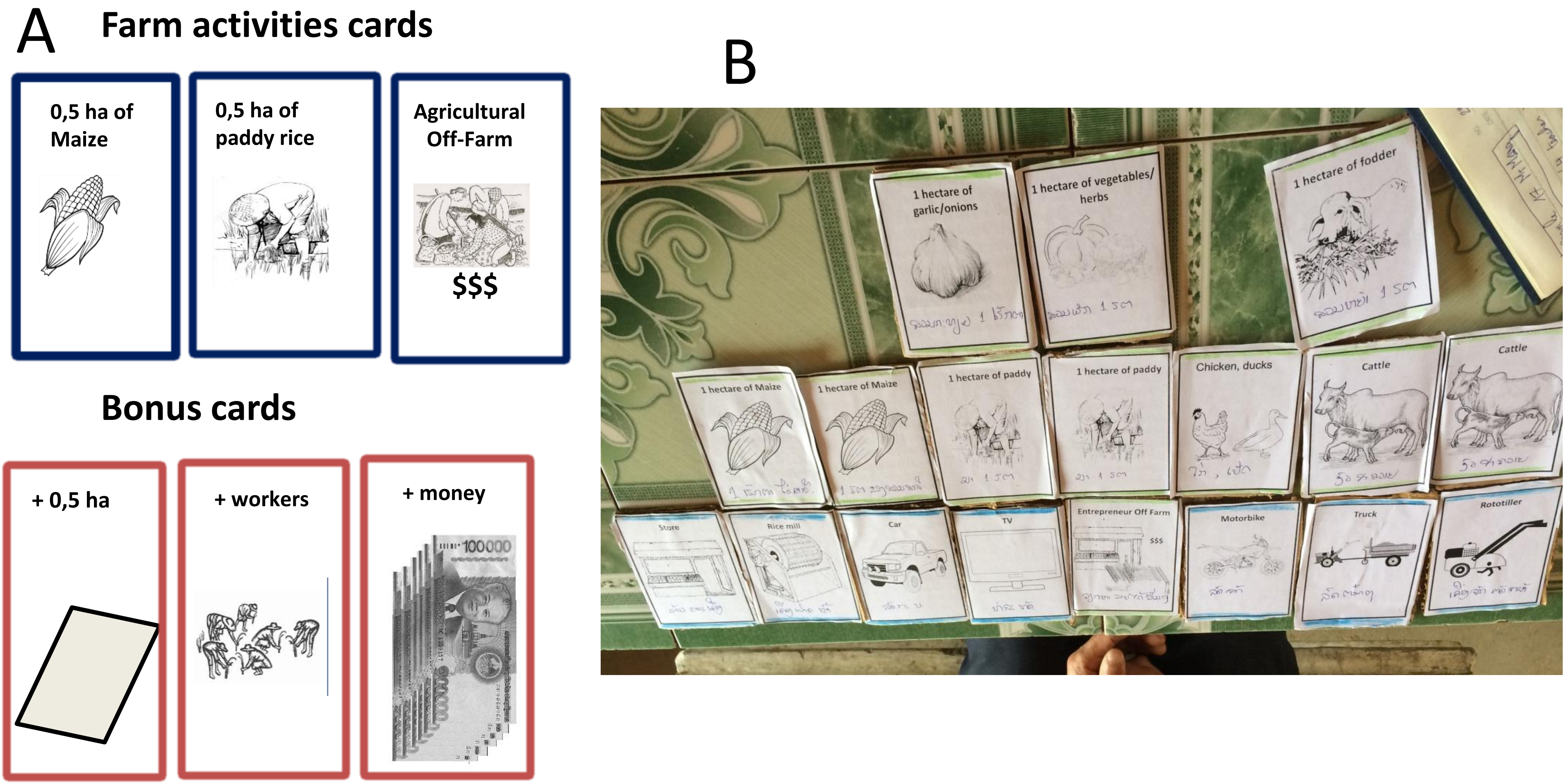

Figure 2: Example of cards used in the individual card game (A) and picture of a deck obtained representing current farmers' activities and assets (B)

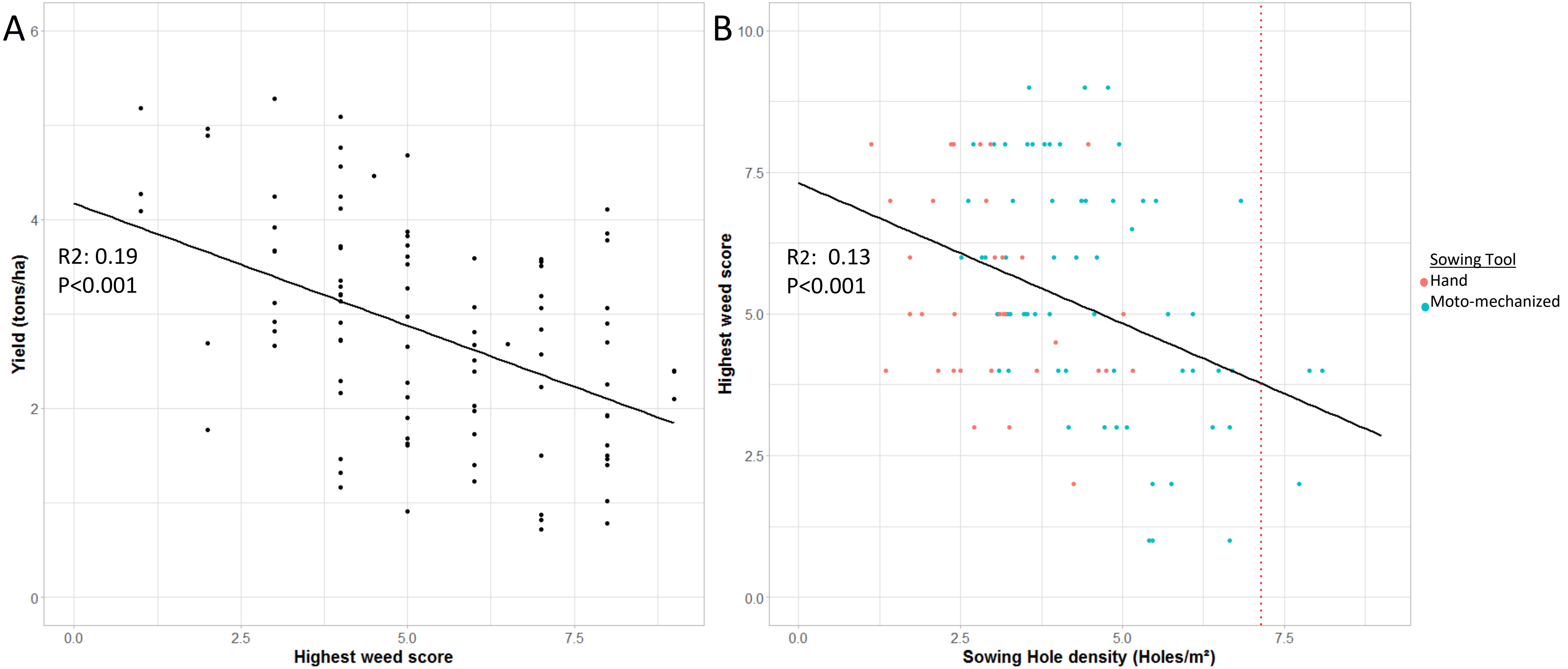

Figure 3: Effect of highest weed score on maize grain yield (3A) and effect of sowing hole density on highest weed score (3B). The red dotted line (3B) is the optimal sowing density allowed by the seed drill (7.1 plants m^{-2})

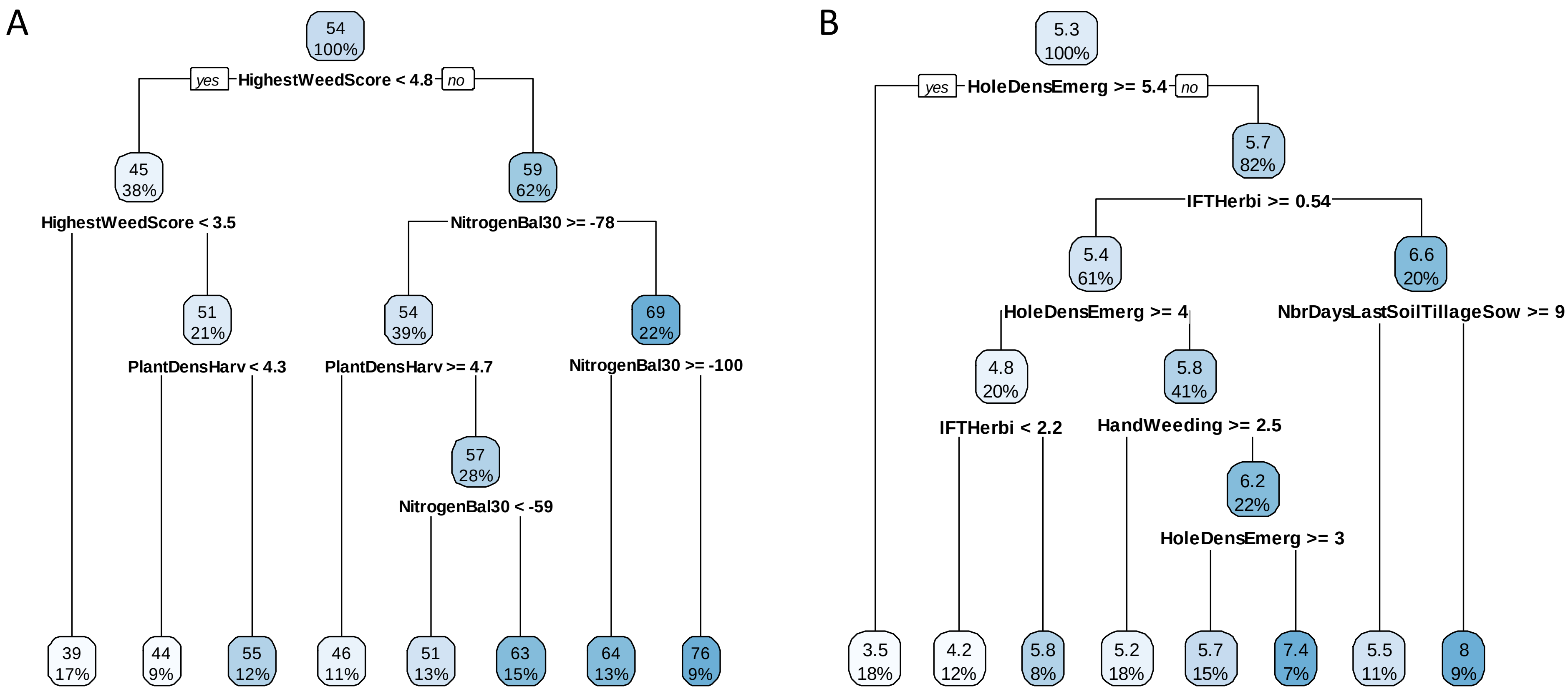

Figure 4: Classification and regression tree models to describe relative yield gap as a function of yield constraining variables (A), and highest weed score as a function of technical management variables (B). In each box, the predicted value is on top and the percentage of observations below. *highestWeedScore*: highest weed score, *NitrogenBal30*: Nitrogen balance (kg ha^{-1}), *PlantDensHarv*: maize plant density at harvest (plant m^{-2}). *IFTHerbi*: Index of herbicide treatment, *HandWeeding*: amount of work dedicated to hand weeding (man day), *HoleDensEmerg*: sowing hole density (holes m^{-2}) and *NbrDaysLastSoilTillageSow*: number of days between last soil tillage and sowing.

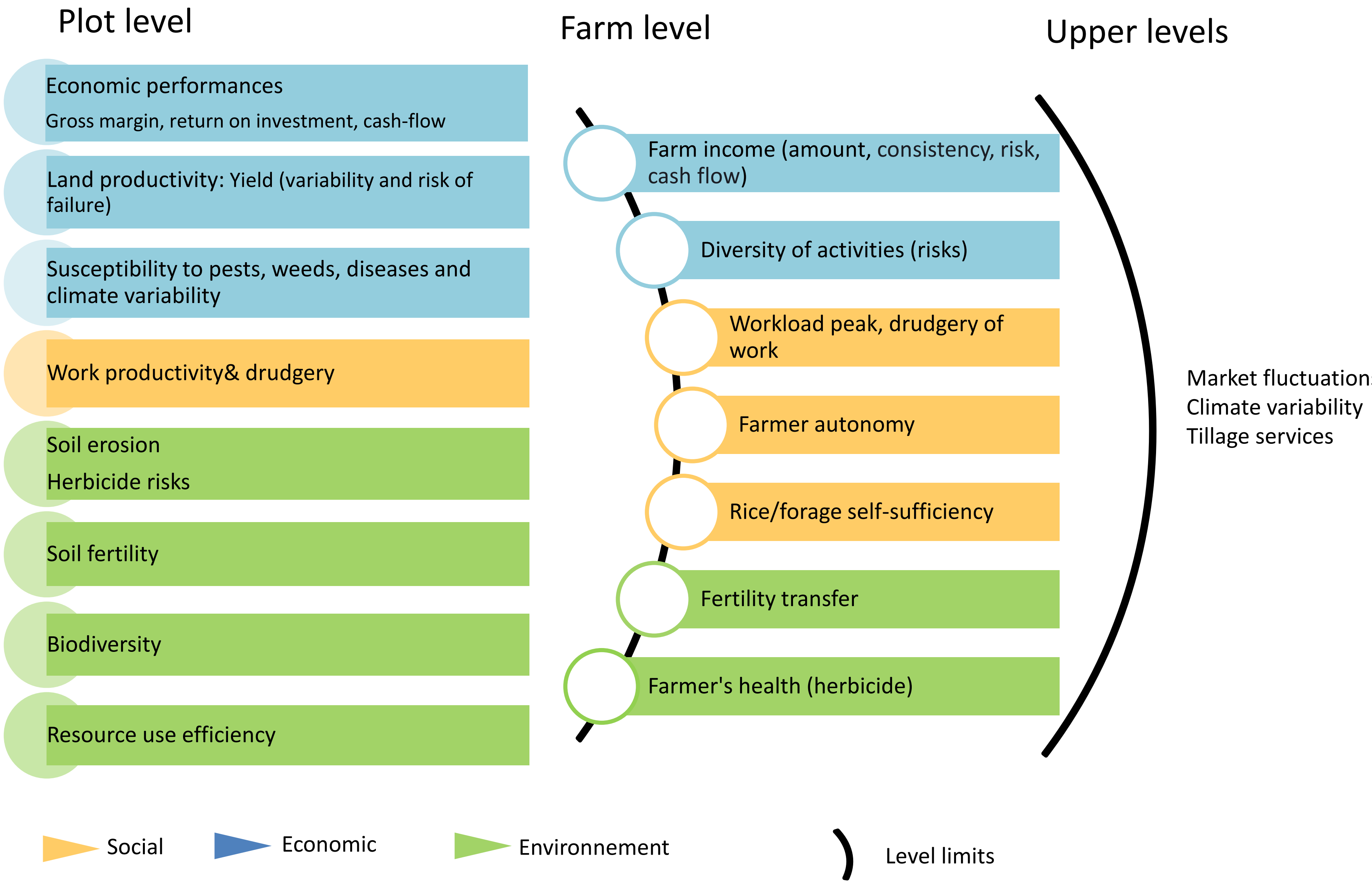

Figure 5: Final set of locally relevant criteria.The reader is referred to the web version of this article for interpretation of references to colors.