

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

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1	Context matters: agronomic field monitoring and participatory research to identify criteria
2	of farming system sustainability in South-East Asia.
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15	Abstract
16	In the mountainous areas of South-East Asia, family farms have shifted from subsistence to
17	input-intensified and market-oriented maize-based farming systems, resulting in a
18	substantial increase in farm income, but also in new environmental threats: deforestation,
19	biodiversity loss, soil erosion, herbicide leaching and soil fertility degradation. In this typical
20	case study of cash-strapped farms, where the balance between socio-economic and
21	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.

24 Serious games at farm level showed that short-term socio-economic dimensions prevailed over environmental dimensions in farmers' objectives. However, farmers also greatly valued 25 26 their capacity to transfer a viable farm to the next generation and avoid herbicide use. 27 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 28 from potential water-limited yield were primarily due to weed infestation favoured by low 29 30 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 31 32 investment for fertilizer, and increased exposure to soil erosion.

33 Combining the perspectives of scientists and farmers led to the following set of locallyrelevant criteria: i) at farm level: farm income, diversity of activities, farmer autonomy, 34 35 farmer health, workload peaks, soil fertility transfer between agroecological zones in the 36 landscape, rice and forage self-sufficiency; ii) at field level: resource use efficiency, soil 37 fertility, erosion and herbicide risks, susceptibility to pests, weeds and climate variability, biodiversity, land productivity, economic performance, labour productivity and work 38 drudgery. Our approach helped to identify key relevant sustainability criteria and could be 39 useful for designing alternatives to current maize-based cropping systems, and contributed 40 41 to informing priority-setting for institutional development and agricultural policies in the 42 region.

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

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47 **1. Introduction**

In recent decades, the productivity and income of smallholder farmers have increased 48 considerably in South-East Asia, thanks to greater market integration (Drahmoune, 2013). 49 The changes in farming systems followed a conventional intensification pathway that 50 mimicked the Green Revolution. Non-irrigable highlands were rapidly converted to maize 51 52 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 53 constrained by cash and labour availability (Jourdain et al., 2020). The shift from subsistence 54 to input-intensified and market-oriented farming systems casts doubts upon farming system 55 sustainability, in relation to (i) economic threats such as input/output price volatility and 56 farmer indebtedness (Hepp et al., 2019) and (ii) environmental threats linked to 57 58 deforestation, biodiversity loss, soil erosion, herbicide leaching and soil fertility degradation (Tivet et al., 2017; Shattuck, 2019; Dupin et al., 2009). 59

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,

65 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 66 expected to face trade-offs between short-term socio-economic objectives (e.g. income, 67 food security) and long-term environmental objectives (e.g. soil fertility, water pollution by 68 pesticides) (Shiferaw and Holden, 1998; Lipton, 1997). This calls for an integrated 69 70 assessment of farming systems that quantifies the trade-offs between socio-economic and 71 environmental dimensions across a set of criteria, to explore the sustainability of agricultural 72 changes (Ness et al., 2007). By "criteria", we mean the issues, themes, principles, goals, "abstract indicators", or attributes describing the sustainability of agricultural systems 73 (different uses of terminology are described in Reed et al., 2006; Binder et al., 2010; 74 75 Niemeijer and de Groot, 2008; de Olde et al., 2016; van Cauwenbergh et al., 2007). Criteria 76 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 77 farming systems) against a set of criteria for decision-support (Boggia and Cortina, 2010; 78 79 Wolfslehner et al., 2012; Sadok et al., 2008). Multi-criteria sustainability assessment is a 80 useful approach when there are multiple, non-commensurate, and possibly conflicting 81 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 82 83 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., 84 2007), RISE (Häni et al., 2003)). Most of the existing approaches assess farming systems 85 86 against a set of criteria meant to be universal. As such, generic tools often contain 87 preconceived ideas of sustainability (Bosshard, 2000) and usually overlook the contextual

88 prioritization emphasized in local sustainability assessments (Barbier and López-Ridaura, 2010; Gasparatos, 2010; Gasparatos et al., 2008). Sustainability is a matter of perspective 89 and relevant criteria often depend on the local context (Zhen and Routray, 2003; Reed et al., 90 2006; Bond et al., 2011; Lairez et al., 2016; Lele and Norgaard, 1996). For example, in a case 91 study of Danish maize value chains for German biogas, Gasso et al. (2015) compared key 92 93 sustainability criteria identified by stakeholders with criteria identified in generic frameworks. They showed that the generic frameworks covered context-specific 94 95 environmental issues, but not context-specific socio-economic issues. Other sustainability assessment methods overcome this weak point by considering farmer and/or stakeholder 96 perspectives to select evaluation criteria (e.g. Roy et al., 2013; Coteur et al., 2016; Coteur et 97 al., 2018; López-Ridaura et al., 2002; Ssebunya et al., 2016; Yegbemey et al., 2014; 98 99 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 100 quantifying and understanding sustainability issues (Fraser et al., 2006). Moreover, the 101 102 span of a farmer's perspective can be incomplete in times of rapid change (Klapwijk et al., 103 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 117 sustainable farming systems, it is necessary to bring together the perspectives of both 118 119 farmers and scientists, because the perspectives of farmers and scientists taken separately 120 are incomplete for dealing with complex sustainability issues. Mixed-method approaches 121 that combine quantitative and qualitative information are helpful in enhancing the understanding of sustainability issues, by providing multiple ways of viewing a problem 122 (Bond et al., 2011; Gough et al., 1998; Creswell and Clark, 2017), and in allowing the 123 strengths of one method to offset the weaknesses of others (Creswell and Clark, 2017). 124 125 The literature is scant on how the knowledge of farmers and scientists can be combined to 126 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 127 perspectives for sustainability assessment seek to select indicators to assess a predefined set 128 of criteria, assuming that sustainability is a generic concept defined with universal criteria. 129

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 134 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 135 farmers' objectives and to understand their priorities and perceptions with regard to 136 sustainability, for farm-level strategic resource allocation and plot-level tactical crop 137 138 management, by way of serious games and Q-methodology, (ii) identify the determinants 139 and criteria of maize cropping system sustainability through a plot-level scientific agronomic 140 diagnosis, and (iii) aggregate farmers' perspectives and insights from the agronomic 141 diagnosis into a set of sustainability criteria that could inform multi-criteria sustainability 142 assessment. The region of Xieng Khouang province in northern Laos was chosen as a typical 143 case study of the market integration of farming systems.

144 **2. Methods**

145 In what follows, we start by describing the overall approach and the study sites (2.1 and 2.2),

146 followed by the methods employed to (i) capture farmers' perceptions of sustainability and

147 (ii) gather scientific insights on sustainability.

148 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 ofsustainability criteria.

158 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 159 160 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 7 161 km² (Figure S1). The villages of Lé, Leng and Dokham were selected because an exhaustive 162 agricultural census was available describing all farm households using basic variables 163 164 (cropped areas, head of cattle and number of people per family). The villages of Xay and 165 Nadou had soils with a high sand content and were added to increase the 166 representativeness of soil type variability.

167 2.2. Site description

We selected the Kham district in Xieng Khouang province located in northern Laos, close to 168 169 the Vietnamese border (19°38'N, 103°33E; 605 m above sea level) (Figure S1, Supplementary 170 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 171 172 extensive manually cultivated upland rice systems to cash crop systems with hybrid maize cultivation, combined with the use of moto-mechanization, herbicides and mineral 173 fertilizers. This rapid switch to maize cultivation was favoured by the increase in maize prices 174 175 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 176 maize cultivation is not sustainable and refer to it as 'resource-mining' agriculture with a 177

178 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 179 literature for Laos, maize cultivation was found to increase production costs 180 (Luangduangsitthideth et al., 2018) and soil erosion (Dupin et al. 2009). In Thailand, Bruun et 181 182 al. (2017) found that maize cultivation had an impact on soil quality. Other studies, analysing 183 farmer perceptions and practices in Laos and the subregion, showed that maize might 184 increase environmental degradation (Kallio et al., 2019; Southavilay et al., 2012; Tuan et al., 185 2014; Epper et al., 2020; Shattuck, 2019). There is nevertheless limited empirical evidence to support claims of environmental degradation (Lestrelin, 2010). 186

187 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 188 slopes (500 to 600 m asl). Lowlands are dedicated to rice cultivation and uplands to forest, 189 pastures and maize cultivation. Hybrid maize is sown once a year during the rainy season 190 (May-October) in sole stands without rotation with other crops. Cultivation starts in early 191 192 April with tillage services using tractors equipped with a disc plough. Maize is either sown 193 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 16-20-194 195 0) mineral fertilizer is used. The herbicides commonly used are atrazine (1-Chloro-3ethylamino-5-isopropylamino-2,4,6-triazine), 196 paraquat (1,1'-Dimethyl-4,4'-bipyridinium dichloride), and glyphosate (*N*-(phosphonomethyl)glycine). Europe banned atrazine in 2003. 197 198 Paraquat was banned in Laos in 2011, but is still sold on local markets by small retailers 199 (Vázquez et al., 2013; Shattuck, 2019).

200 2.3. Farmer perspective: serious games and Q-methodology

201 We used two types of serious games to reveal farmers' objectives. The participation level 202 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 203 204 two levels of decision-making: (i) farm-level strategic resource allocation and (ii) plot-level 205 tactical crop management. We first played an individual card game to identify farmers' 206 objectives (farm level), and then a group game to identify farmers' important attributes for 207 deciding which crop to grow (field level). The impact on soil fertility emerged as an 208 important attribute during the group game. We therefore used a Q-methodology survey 209 (Alexander et al. (2018) and Pereira et al., (2016)) to deepen our understanding of farmers' 210 perception of soil fertility.

211 Individual card game to determine famers' objectives

212 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 213 214 Rodriguez-Ocana (1998), we related farmers' objectives to "values" that guide action or 215 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 216 217 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 218 219 traditions, working with the family, respecting the village committee decisions, or doing 220 what others do. (3) *Expressive values*, e.g. gaining self-respect, meeting a challenge. (4) 221 Intrinsic values, e.g. enjoying working tasks, preferring healthy practices, valuing hard work, 222 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 227 228 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, 229 such as a labour workforce, land and money (Figure 2A). In a first step, the farmers were 230 231 invited to discover and understand the cards. Then, each farmer was asked to tell the story 232 of their farm and to explain the main choices they had had to make since they had become 233 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 234 activity and asset cards. The farmer was invited to validate or modify the deck to get 235 accustomed to the use of the cards. The card combination at the end of the game 236 237 represented the current farm situation (see example in Figure 2B). In a second phase, the 238 farmer was invited to expose and explain their future five-year perspective with cards. Then, 239 the interviewer substituted some activities by others to provoke the farmer's reaction. If the 240 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 241 finishing the game with only a list of farmers' constraints rather than farmers' objectives. In 242 243 a final step, the interviewer reformulated farmer choices and reactions until a list of 244 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 245

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).

249 *Group game on important crop attributes*

250 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. 251 252 (2018). The game was played once per village in Lé, Leng and Xays, gathering 15-20 people in 253 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 254 255 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 256 257 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 258 259 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. 260 261 Then the participants voted for three questions by giving a score from 3 (most important) to 262 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 263 the yellow beverage was replaced by a fictional crop as it helped farmers to understand how 264 265 to ask questions with yes/no answers. The second step was a real game focusing on the 266 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 267 268 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.

276 Soil fertility perception: Q-methodology

Q-methodology was not directly used to identify criteria, but rather as a complementary 277 278 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 279 280 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 281 282 with soil fertility by confronting them with a Q-set, i.e. a sample of 47 statements 283 representing contrasting narratives on soil fertility (Table S1 and Figure S2 in Supplementary 284 material). Statements were selected to maximize the diversity of opinions about soil fertility 285 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 286 287 sample maximized the diversity of soil types and degree of intensification in maize cropping 288 systems. The Q-methodology was carried out individually with each farmer. Statements 289 were written on cards in the Lao language and the interviewer first read all the cards to 290 allow the farmer to ask questions for clarification. The farmers were first asked to divide the 291 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 lofrida *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).

303 2.4. Researcher perspective: agronomic diagnosis

304 *Field monitoring network*

To identify plot-level sustainability criteria, farmer-managed fields were monitored from 305 306 2016 to 2018 following the method of Doré et al. (1997). Contrasting plots in the farmers' 307 maize fields were monitored. Firstly, participatory maps of low/high yielding areas, 308 biophysically contrasting zones and crop management (Mascarenhas and Kumar, 1991) were 309 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 310 three villages to draw up these participatory maps. The fields where then selected to ensure 311 312 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 313

314 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 315 of 3 to 5 m. We monitored 38 plots in 2016, 38 plots in 2017, and 35 plots in 2018 (n=111). 316 317 For each cropping season, plots were located in 15 farm fields, i.e. more than one plot per 318 field depending on within-field soil and crop management heterogeneity. Table 1 shows the 319 monitored variables. Due to losses at harvest, 99 plots (out of 111) had observations for all 320 the variables monitored: weed cover, pests, nutrient deficiency, yield components, crop 321 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.

329 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

336 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 337 yield achieved when water and nutrient supplies exceed crop requirements and biotic 338 339 stresses are absent. Factors determining potential yield are incoming solar radiation, 340 temperature, atmospheric [CO₂], crop genetic characteristics and canopy light interception 341 ability (van Ittersum and Rabbinge, 1997; van Ittersum et al., 2013). Yw is similar to YO, but 342 with actual water supply that may limit crop growth (van Ittersum *et al.*, 2013). Table 2 gives 343 more details on the calculation of the variables related to agronomic performance. The 344 herbicide treatment index and erosion risks approximated with the length of the bare-soil 345 period from ploughing to sowing, N balance and fertilizer doses, were considered as variables related to environmental performance (Table 2). 346

A first analysis looked at relating maize yield to the variables deemed important for 347 agronomic performance (Table 2), i.e. single factor linear regressions of yield against water 348 stress, potential N balance, and pest/weed scores. In a second analysis, two classification 349 350 and regression tree (CART) models (Delmotte et al., 2011; Tittonell et al., 2008) were built (R 351 software Rpart package, Terry Therneau and Beth Atkinson (2019)). The first CART aimed at 352 identifying the main factors explaining yield variability. It was built on the total dataset 353 (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 354 score, maize planting density, N balance and soil type. The second CART was performed with 355 356 the main factor explaining yield gap variability (identified with the first CART) as the target 357 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 358

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).

362 Eventually, selection of the main drivers of variability in performance and impacts informed363 the creation of the sustainability criteria to be selected.

364 **3. Results**

365 3.1. Serious games and Q-methodology

366 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:

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

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

387 The objective "to be able to transfer a viable farm to the next generation" was related to 388 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 389 used as a criterion because (i) it was mentioned by only a small number of farmers (7%) and 390 (ii) "traditional activity" would be hard to quantify. We did not consider the objective 391 "perform activities that are easily manageable" as a specific criterion, but it was included in 392 393 the criteria "farm income - amount, consistency, cash-flow and risks" and "workload peak, 394 drudgery of work". Indeed farmers during the group game revealed their fear of financial 395 loss resulting from inadequate crop management and their reluctance to devote to a crop a 396 large amount of work with too many interventions (see section below).

397

398 *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

402 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 403 villages (score of 27 in Leng, 6 in Lé, while soil fertility was evoked through the ability of the 404 405 new crop to be easily grown on village soil types in Xay). High crop yield was important in 406 Xay (score: 30), whereas in Leng a good selling price and market channel availability were 407 scored higher than yield. In the fourth step of the game, farmers explained that the "ease of 408 crop management" attribute originated from (i) their fear of financial loss resulting from 409 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' 410 411 wish to control the selling period and prices.

412 We determined five plot-level criteria by aggregating the attributes that mattered to 413 farmers:

414 1) "Economic performance - gross margin, return on investment, cash-flow and risk"
415 (from the questions "Does it have a high yield?", "Does the crop have a good selling
416 price?", "Does it have a good market (lot of buyers)?", "Is it expensive to grow it?",
417 "Can we get a good benefit from it?", "Is the price stable?" and "Does it require a lot
418 of fertilizer?")

419 2) Land productivity (from the question "Does it have a high yield?")

420 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 forvillage 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.

434 *Q*-methodology on soil fertility perception

435 Farmers agreed on five statements regarding soil fertility (Table 4): "The soil is fertile when it 436 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 437 438 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 439 is fertile" (47% of farmers), "Low crop yield in a good climatic year is an indicator of low 440 441 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 442 could give more yield today thanks to mineral fertilizer, a good variety and herbicide" (42% 443 444 of farmers), "Low maize density is the main cause of low yield compared with low soil fertility" (42% of farmers). 445

446 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 447 has a black colour, it is a fertile soil, and if the soil is red or yellow it is an infertile soil", and 448 (iii) "Soil fertility has decreased because of ploughing every year". They disagreed with 449 450 "Farming practices today will impact the future generations, but there is no other 451 alternative". Farmers with opinion 1 were slightly more concerned by long-term issues than 452 the others, since the statement "I want to preserve the fertility of my soil for the future farm 453 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, 454 "Income-minded" farmers (opinion 2-O2, Table 4) attached more importance to soil 455 456 structure after ploughing and disagreed strongly with the statement "Farmers have a duty to 457 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 458 colour and the structure of the soil, a fertile soil has a high yield without adding mineral 459 460 fertilizer". "No-alternative" farmers (opinion 3-O3, Table 4) agreed that (i) "Farming 461 practices today will impact the future generations, but there is no other alternative", (ii) "A 462 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 463 464 statement). They disagreed with (i) "A fertile soil is a soil where it is easy to obtain a 465 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 466 467 fertility criteria were not necessarily related to short-term income maximization in farmer's 468 minds. Interestingly, the Q-methodology showed that a group of farmers expressed a

469 complex perception of soil fertility beyond a mere concern for high yields and immediate
470 profits, i.e. they were willing to preserve it for future generations. Even *"income-minded"*471 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.

477

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.

484 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

492 harrowing, herbicide or fertilizer) and low-input intensified systems (hand sowing, no 493 harrowing and herbicide). The participatory mapping combined with the review of local 494 knowledge and field visits helped identify the following criteria to select the plots to 495 monitor: farmer-reported yields, slope, level of agricultural intensification, soil type and soil 496 quality as visually appraised by the farmer.

497 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 498 time between soil preparation and sowing. Clayey-loamy soils, the dominant soil type in the 499 500 monitored plots, had, on average, an organic nitrogen content of 0.096%, a soil organic 501 matter content of 2.44%, a total cationic exchange capacity of 9.7 me/100g and a pH of 6.01 502 (see Figure S3 for detailed results of soil analysis and soil type). Herbicide application varied 503 greatly (Table 5). The herbicide treatment index for cropping system 3 (moderate slopes, 504 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 505 506 system 4 (flat land, mechanical sowing on clayey-loamy soils, medium period of bare soil). 507 Fertilization rates were low with 20 kg of N ha⁻¹, on average, in fertilized plots and never 508 exceeded 40 kg N ha⁻¹. The potential N balance was below -10 kg ha⁻¹ for 90% of the plots 509 (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 510 erosion were either due to slopes or due to a long period between ploughing and sowing. 511 512 The number of days between ploughing and sowing varied from 3 to 108 and averaged 29 513 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-bedpractice to reduce weed pressure.

516 The average potential (YO) and water limited (Yw) yields were 6.2 t ha⁻¹ and 6.0 t ha⁻¹, 517 respectively, for the 111 plots simulated with the crop model. The limited difference 518 between YO and YW indicated a low impact of water stress on yields in the monitored plots. 519 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, 520 respectively. The observed maize yields (Ya) in the monitored plots were markedly below Yw 521 522 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 523 all, 25% of the plots had a yield below 1.9 t ha⁻¹. The relative yield gap ranged from 8% to 524 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, 525 itself mainly explained by sowing hole density. Yields were correlated to "Highest weed 526 527 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 528 529 competition with weeds in our context, sowing hole density mattered more than plant 530 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 531 to a plant density double that achieved with the seed drill, but with the same space (and 532 light for weeds) between holes. Sowing hole density varied greatly from 1.1 to 8.1 sowing 533 holes m⁻². A higher sowing hole density was achieved with mechanical sowing compared 534 535 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.

538 In CART, "Highest weed score" was the main variable explaining relative yield gap variability 539 (Figure 4A). The plot relative yield gap (Yr) was categorized in eight groups (R²=0.37) 540 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" 541 above 4.8, and 45% for plots below 4.8. For plots with a high weed score, Yr was 69% when 542 the potential N balance was below -78 kgN ha⁻¹ and 54% when the N balance was above that 543 544 threshold. Similar interpretations could be derived by reading the other branches of the 545 tree. Weed infestation variability was first explained by sowing hole density (Figure 4B), 546 followed by herbicide doses and number of days between the last soil tillage and sowing (R²=0.47). 547

The key outcomes revealed by the agronomic diagnosis were: i) high yield variability, high 548 549 yield gaps and a high risk of failure, ii) low sowing density leading to: high weed pressure, 550 low yields, low resource use efficiency, a high workload for weeding and a low return on 551 cash investment, iii) herbicide overuse and leaching risks due to weed infestation, iv) erosion 552 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 553 maize fields were used for cattle roaming in the dry season and the manure collected at 554 555 night was exclusively used for lowland rice.

556 The outcomes of the agronomic diagnosis informed the determination of the following plot-557 level criteria: 1) Land productivity: yield variability and risk of failure, 2) Soil erosion, 3)

558 Susceptibility to weeds, 4) Resource use efficiency, 5) Work productivity and drudgery, 6) 559 Herbicide risks, 7) Economic performance. At farm level the agronomic diagnosis informed 560 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.

566 3.3. Integration of knowledge to select the final set of criteria

567 Plot-level sustainability criteria

Figure 5 shows the final set of criteria resulting from an integration of farmer and scientist 568 perspectives. Every criterion identified can be quantified with indicators. On the left-hand 569 570 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 571 productivity, susceptibility to pests, weeds, diseases and climate variability, work 572 573 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 574 games were grouped with those from the agronomic diagnosis, e.g. "economic 575 performance" includes gross margin (derived from the TAKIT game), return on investment 576 (derived from the agronomic diagnosis and the TAKIT game) and cash flow (derived from the 577 578 card game and the TAKIT game).

579 Farm-level sustainability criteria

580 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 581 (amount, consistency, risk and cash flow), diversity of activities (risks), workload peak, 582 drudgery of work, farmer autonomy, rice/forage self-sufficiency, fertility transfer, and 583 584 farmer's health risks due to herbicides. To establish this final list, the criteria originating from 585 the serious games were grouped with those from the agronomic diagnosis, e.g. farmer 586 health includes herbicide overuse (derived from agronomic diagnosis) and farmers' concerns 587 when spraying herbicide (derived from the card game).

588 **4. Discussion**

589 4.1. Strengths and pitfalls of each part of the method

590 Long-term perspective with serious games and Q-methodology

591 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 592 593 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, 594 however, have been due to a desirability bias, i.e. the tendency of farmers to answer 595 596 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 597 from an international agricultural research centre and did not put any particular emphasis 598 599 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 600 601 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 maizebased systems. Unravelling the factors driving maize cropping system sustainability was crucial.

608 Drivers of cropping systems sustainability with the agronomic diagnosis

609 Maize cropping system performance varied widely, but single factors (weed and pest competition, N balance, and water stress) explained only 19% (r²=0.19) of the variations (at 610 611 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 612 613 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 614 615 pressure over soil fertility to explain yield variability. Soil fertility remains an issue for the 616 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) 617 618 density drive maize cropping system sustainability. With mechanical sowing, the low sowing 619 density was probably due to a malfunctioning of the seed drill. The seed drill opens by 620 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-621 622 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 623 624 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.

628 Direct measurements are more time-consuming and cost-intensive than rapid farmer 629 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 630 implement it quickly over one or two cropping seasons. However, in line with our objective 631 to publish a scientific paper, plot monitoring was carried out over three cropping seasons, 632 633 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 634 635 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 636 multi-criteria assessment at farm level and were the basis for the quantification of indicators 637 at that level. 638

639 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).

645 Integration of multiple perspectives

646 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 647 made it possible to embrace the plurality of views on sustainability. Scientific analyses at 648 649 plot level were useful for explaining and understanding the biophysical processes at stake in 650 sustainability issues. Qualitative data from the serious games and Q-methodology at plot 651 and farm levels were useful for understanding farmers' perceptions, objectives and 652 concerns. The two types of knowledge taken separately would have been incomplete for 653 determining relevant criteria, because: i) quantitative insights obtained in field monitoring lacked farm-scale contextualization integrating farmers' decisions and constraints; ii) 654 655 qualitative insights gained through the serious games were village-specific and difficult to 656 generalize. Field monitoring therefore helped in understanding certain outputs of the 657 serious games results.

658 Combining the two perspectives, we showed that farmers' willingness to maintain soil fertility contrasted with current soil management associated with negative N balances and 659 660 risks of erosion. Field monitoring showed that, in the current state of maize cropping 661 systems, it was probably not profitable for farmers to invest time and money for fertility 662 management in fields with poor crop performance, partly due to poor crop establishment 663 and the resulting weed pressure. Our study revealed discrepancies between farmers' perspectives and agronomic facts: farmers generally disagreed with the statement "Low 664 maize density is the main cause of low yield compared with low soil fertility" (See section 665 666 3.1), while field monitoring revealed the crucial role of a low plant density and subsequent 667 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 668

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.

683 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.

694 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.

701 Our approach highlighted the role of science and the importance of quantitative data for 702 understanding sustainability, a value-based concept. Any scientific assessment has assumptions, values or preferred fields of interest (Sala et al., 2015). Indeed, 20th century 703 704 epistemologists dispelled the idea that scientists are devoid of value, independent and 705 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 706 707 the scientific community and farmers. Our experimental design swept aside preconceived 708 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

712 makes them inappropriate for understanding drivers of sustainability. Our approach
713 combined credible agronomic information and farmers' perspectives with logical reasoning.

714 **5. Conclusion**

715 Over a period of three years we applied a multi-level and multi-method approach that 716 combined farmers' and researchers' perceptions of sustainability in northern Laos. This 717 study contributes to the need to integrate farmers' and scientists' views and opinions on 718 sustainability, as each vision is incomplete without the other. Several complementary 719 analyses, from plot to farm level, helped to identify a set of locally relevant sustainability 720 criteria. These criteria can be used to compare different farming systems in relation to their 721 sustainability. The list of criteria identified in this study is currently being used to explore 722 with ex-ante farm modelling pathways, to improve the sustainability of maize-based systems 723 in the region.

We found that, beyond the standard socio-economic criteria expected for poor farmers, 724 725 farmers also valued other long-term sustainability criteria (e.g. transfer a viable farm, 726 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 727 728 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 729 730 revealed that it is mainly inadequate crop management during crop installation that leads to 731 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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1060 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		Field observation
Disease and pest severity score	Score from 1 to 5	Every month	FIEID ODSERVATION
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		
Soil management (labour requirement)	Man-days		
Herbicide applications (type of product and	Date		
date)			
Herbicide applications (amount)	kg or litres	After each field operation	F
Fertilizer applications (type of product and	Date		Farm surveys
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	
Textural and chemical analysis	0 1	0	
- Cationic exchange capacity	me/100g		
- Soil texture (sand, silt, clay)	%		Lab analysis
- Organic matter	%		,
- Total nitrogen	‰	Once in 2017 before growing	
- Total phosphorus	%0	season	
- pH	-		
Weather data			
Rain	mm		
Temperature	°C		Comphall station :
Humidity	%	Every nour during growing	Campbell station +
Global radiation	kW m⁻²	season	Tinytag
Wind	m s ⁻¹		

- 1063 Table 2: Variables used to explain plot-level agronomic and environmental performance (with units in
- 1064 brackets). Yw: potential water-limited yield, Ya: observed actual yield, LAIw: Leaf Area Index, water limited,
- 1065 LAIO: potential Leaf Area Index, YO: potential yield, Nmin: nitrogen mineralized from total soil organic nitrogen
- 1066 (kg ha⁻¹), *Nfert*: amount of mineral nitrogen applied (kg ha⁻¹), *Nuptake*: nitrogen uptake from soil by maize (kg
- 1067 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 (-)	Alw/I Al0	PYF model
		simulation
	Yw/Y0	
Potential nitrogen balance (kg	Nmin + Nfert – Nuptake	Direct
ha-1)		measurement;
Quantity of nitrogan potentially		PYE model
left in the coil for maize violding	Where	simulation;
at water limited potential		QUEFTS
at water-innited potential		equation
		outputs
	-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)	
	-Nuntake= Yw*21 (21 is N (ka) taken un per top of maize arain at	
	12% humidity Standford (1973) assumed for a maize vielding at	
	6 278 tons/hg)	
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	Observation
	Highert wood score (from 20 days after souring to harvest) 1 to 0	
Pest damage severity score	Score, 1 to 5	Observation
(number)		
Environmental performance		
Herbicide treatment index	HTI= (applied dose)/(recommended dose* area of the field)	Farmer survey
(HTI) (number of		
recommended doses)		
Erosion risk (number)	Number of days between plougning and sowing	Farmer survey
Potential nitrogen balance (kg	See above	See above
ha ⁻¹)		
Nineral fertilizer use (Kg.ha-1)	Doses	Farmer survey

- 1068 Table 3: Farmers' objectives and important crop attributes resulting from card and group games carried out
- 1069 with farmers in three villages of northern Laos. For the group game the final score was obtained by summing
- 1070 the scores given by farmers in a given village (see section 2.2).

Village	Farmers' objectives (five-year perspective) (card game)	% farmers
	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%
Lé, leng, Xay	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	Score
	"I am a trader and I have the best upland crop ever, what question would	
	Is it suitable for village soils?	28
	Does it improve the soil?	20
	Does the crop have a good calling price?	27
	Does it have a good market (lot of huvers)?	5
Leng	Does it have a good market (lot of buyers):	5
	Is it expensive to grow it?	
	Can the project help us for the implementation?	0*
	Is it a crop susceptible to post?	0*
	Is it storable?	20
	Is it eacy to grow?	20
	Does it require a lot of labour?	20
	Does it have a good market (lot of huvers)?	,
	Does it improve the soil?	6
١ó	Does the grap have a good calling price?	5
Le	Is it suitable for village soils?	2
	Can we use it for our own consumption?	2
	Doos it require a lot of fortilizer?	3 1
	Does it have a good vield?	2
	Can we get a good henefit from it?	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
		Does it have a good yield?	30
		Is it easy to grow?	15
		Do technicians recommend us to grow it?	12
	Хау	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
1071	*the question was	mentioned in the preliminary steps but no farmers finally ranked it as important	5
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- 1090 Table 4: Farmers' soil fertility perception based on a sample of statements representing contrasting narratives
- 1091 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.

	01	. 02	03		
Statements for which most farmers disagreed (no statistical difference at 95% between opinions)					
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% betwee	n opiı	nions)		%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	2	-4	2	
on today's profits	۷	-	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			2	
Cultivation	-1	-4	-2	
on today's profits	2	-4	2	
Statements describing O2	_		-	
Statements describing US				
- For which there is a statistical difference with O1 and O2				
For which there is a statistical difference with O1 and O2 Farming practices today will impact the future generations, but there is no other				
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	
- 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 A fertile soil is mellow and has a good structure after ploughing	-2 0	0	4 3	
- 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 A fertile soil is mellow and has a good structure after ploughing A fertile soil is a soil where it is easy to obtain a satisfactory plant density at	-2 0	0	4 3	
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 A fertile soil is mellow and has a good structure after ploughing 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 0 2	0 5 3	4 3 -2	
- 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 A fertile soil is mellow and has a good structure after ploughing A fertile soil is a soil where it is easy to obtain a satisfactory plant density at emergence even if rainfall events are scarce A fertile soil is a soil where it is easy to obtain a satisfactory plant density at	-2 0 2	0 5 3	4 3 -2	
- 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 A fertile soil is mellow and has a good structure after ploughing A fertile soil is a soil where it is easy to obtain a satisfactory plant density at emergence even if rainfall events are scarce A fertile soil is a soil where it is easy to obtain a satisfactory plant density at emergence with a seed drill	2 0 2 0	0 5 3 3	4 3 -2 -3	
- 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 A fertile soil is mellow and has a good structure after ploughing A fertile soil is a soil where it is easy to obtain a satisfactory plant density at emergence even if rainfall events are scarce A fertile soil is a soil where it is easy to obtain a satisfactory plant density at emergence with a seed drill The use of herbicides makes the soil less fertile	2 0 2 0 0	0 5 3 3 -2	4 3 -2 -3 -4	
- 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 A fertile soil is mellow and has a good structure after ploughing A fertile soil is a soil where it is easy to obtain a satisfactory plant density at emergence even if rainfall events are scarce A fertile soil is a soil where it is easy to obtain a satisfactory plant density at emergence with a seed drill The use of herbicides makes the soil less fertile - Most agreed statements	2 0 2 0 0	0 5 3 -2	4 3 -2 -3 -4	
- 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 A fertile soil is mellow and has a good structure after ploughing A fertile soil is a soil where it is easy to obtain a satisfactory plant density at emergence even if rainfall events are scarce A fertile soil is a soil where it is easy to obtain a satisfactory plant density at emergence with a seed drill The use of herbicides makes the soil less fertile - Most agreed statements The soil is fertile when it gives enough food to the plants to grow without mineral fertilizer addition	2 0 2 0 0 5	0 5 3 3 -2 4	4 3 -2 -3 -4 5	
Statements describing OS - 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 A fertile soil is mellow and has a good structure after ploughing A fertile soil is a soil where it is easy to obtain a satisfactory plant density at emergence even if rainfall events are scarce A fertile soil is a soil where it is easy to obtain a satisfactory plant density at emergence with a seed drill The use of herbicides makes the soil less fertile - Most agreed statements The soil is fertile when it gives enough food to the plants to grow without mineral fertilizer addition Soil erosion leads to a decline in fertility because the most fertile layer disappears	2 0 2 0 0 0 5 2	0 5 3 3 -2 4 3	4 3 -2 -3 -4 5 5	
- 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 A fertile soil is mellow and has a good structure after ploughing A fertile soil is a soil where it is easy to obtain a satisfactory plant density at emergence even if rainfall events are scarce A fertile soil is a soil where it is easy to obtain a satisfactory plant density at emergence with a seed drill The use of herbicides makes the soil less fertile - Most agreed statements The soil is fertile when it gives enough food to the plants to grow without mineral fertilizer addition Soil erosion leads to a decline in fertility because the most fertile layer disappears Soils in flat land cleared from very old forest remain fertile even after 15 years of	2 0 2 0 0 5 2	0 5 3 -2 4 3	4 3 -2 -3 -4 5 5	
- 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 A fertile soil is mellow and has a good structure after ploughing A fertile soil is a soil where it is easy to obtain a satisfactory plant density at emergence even if rainfall events are scarce A fertile soil is a soil where it is easy to obtain a satisfactory plant density at emergence with a seed drill The use of herbicides makes the soil less fertile - Most agreed statements The soil is fertile when it gives enough food to the plants to grow without mineral fertilizer addition Soil erosion leads to a decline in fertility because the most fertile layer disappears Soils in flat land cleared from very old forest remain fertile even after 15 years of maize cultivation	-2 0 2 0 0 0 5 2 2 3	0 5 3 3 -2 4 3 4	4 3 -2 -3 -4 5 5 5 4	
 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 A fertile soil is mellow and has a good structure after ploughing A fertile soil is a soil where it is easy to obtain a satisfactory plant density at emergence even if rainfall events are scarce A fertile soil is a soil where it is easy to obtain a satisfactory plant density at emergence with a seed drill The use of herbicides makes the soil less fertile Most agreed statements The soil is fertile when it gives enough food to the plants to grow without mineral fertilizer addition Soil erosion leads to a decline in fertility because the most fertile layer disappears Soils in flat land cleared from very old forest remain fertile even after 15 years of maize cultivation It is important to prevent soil fertility loss even if we have to work more by doing so 	2 0 2 0 0 0 5 2 3 1	0 5 3 3 -2 4 3 4 -1	4 3 -2 -3 -4 5 5 5 4 4 4	
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 A fertile soil is mellow and has a good structure after ploughing A fertile soil is a soil where it is easy to obtain a satisfactory plant density at emergence even if rainfall events are scarce A fertile soil is a soil where it is easy to obtain a satisfactory plant density at emergence with a seed drill The use of herbicides makes the soil less fertile - Most agreed statements The soil is fertile when it gives enough food to the plants to grow without mineral fertilizer addition Soil erosion leads to a decline in fertility because the most fertile layer disappears Soils in flat land cleared from very old forest remain fertile even after 15 years of maize cultivation It is important to prevent soil fertility loss even if we have to work more by doing so - Most disagreed statements	2 0 2 0 0 0 5 2 3 1	0 5 3 3 -2 4 3 4 -1	4 3 -2 -3 -4 5 5 5 4 4 4	
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 A fertile soil is mellow and has a good structure after ploughing A fertile soil is a soil where it is easy to obtain a satisfactory plant density at emergence even if rainfall events are scarce A fertile soil is a soil where it is easy to obtain a satisfactory plant density at emergence with a seed drill The use of herbicides makes the soil less fertile - Most agreed statements The soil is fertile when it gives enough food to the plants to grow without mineral fertilizer addition Soil erosion leads to a decline in fertility because the most fertile layer disappears Soils in flat land cleared from very old forest remain fertile even after 15 years of maize cultivation It is important to prevent soil fertility loss even if we have to work more by doing so - Most disagreed statements Fertilizer and cow manure are the same for fertility improvement	-2 0 2 0 0 0 5 2 3 1 -3	0 5 3 -2 4 3 4 -1 -2	4 3 -2 -3 -4 5 5 5 5 4 4 4 4 -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 environn	nental 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				

- 1 Table 6: Variability in measured maize yield, relative yield gap, plant density and sowing hole density in the
- 2 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
	1 st Quartile	1.9	42	3.5	3.1
	Median	2.8	54	4.3	3.9
	Mean	2.8	54	4.5	4.1
	3 rd Quartile	3.6	68	5.3	4.9
	Max.	5.3	89	7.5	8.1
3					Ι
4					
5					
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Figure 1: General approach of this study to identify complementary perspectives and determine a set of locally relevant sustainability criteria.

A Farm activities cards





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.