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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

22 (serious games and Q-methodology), combined with agronomic field monitoring, to identify
23 relevant farm and field-level criteria for sustainability assessment.

24 Serious games at farm level showed that short-term socio-economic dimensions prevailed
25 over environmental dimensions in farmers' objectives. However, farmers also greatly valued
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
28 for future generations. The agronomic field monitoring showed that maize yield deviations
29 from potential water-limited yield were primarily due to weed infestation favoured by low
30 sowing density, due to uncontrolled moto-mechanized crop establishment. This technical
31 failure at the beginning of the maize cycle led to herbicide overuse, poor returns on
32 investment for fertilizer, and increased exposure to soil erosion.

33 Combining the perspectives of scientists and farmers led to the following set of locally-
34 relevant criteria: i) at farm level: farm income, diversity of activities, farmer autonomy,
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,
38 biodiversity, land productivity, economic performance, labour productivity and work
39 drudgery. Our approach helped to identify key relevant sustainability criteria and could be
40 useful for designing alternatives to current maize-based cropping systems, and contributed
41 to informing priority-setting for institutional development and agricultural policies in the
42 region.

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

45

46

47 **1. Introduction**

48 In recent decades, the productivity and income of smallholder farmers have increased
49 considerably in South-East Asia, thanks to greater market integration (Drahmoune, 2013).

50 The changes in farming systems followed a conventional intensification pathway that
51 mimicked the Green Revolution. Non-irrigable highlands were rapidly converted to maize
52 mono-cropping (Kong *et al.*, 2019), driven mostly by the high profitability of animal feed
53 production for a growing meat market. Despite these trends, farmers in Laos are still
54 constrained by cash and labour availability (Jourdain *et al.*, 2020). The shift from subsistence
55 to input-intensified and market-oriented farming systems casts doubts upon farming system
56 sustainability, in relation to (i) economic threats such as input/output price volatility and
57 farmer indebtedness (Hepp *et al.*, 2019) and (ii) environmental threats linked to
58 deforestation, biodiversity loss, soil erosion, herbicide leaching and soil fertility degradation
59 (Tivet *et al.*, 2017; Shattuck, 2019; Dupin *et al.*, 2009).

60 The sustainability concept is multidimensional and embodies ecological, economic and social
61 dimensions (Hansen, 1996; Binder *et al.*, 2010). Analysing farming system sustainability in
62 South-East Asia along these dimensions is crucial for taking up the challenges ahead for
63 these farming systems, and for identifying their strengths and weaknesses. In developing
64 countries sustainable agriculture embodies natural resource and ecosystem preservation,

65 enhances resiliency to change and is the driver for improving food security and poverty
66 reduction (Schindler *et al.*, 2015; Schader *et al.*, 2014). Poor smallholder farmers are
67 expected to face trade-offs between short-term socio-economic objectives (e.g. income,
68 food security) and long-term environmental objectives (e.g. soil fertility, water pollution by
69 pesticides) (Shiferaw and Holden, 1998; Lipton, 1997). This calls for an integrated
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,
73 “abstract indicators”, or attributes describing the sustainability of agricultural systems
74 (different uses of terminology are described in Reed *et al.*, 2006; Binder *et al.*, 2010;
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
77 indicators. Multi-criteria tools are used to compare alternatives (e.g. different cropping or
78 farming systems) against a set of criteria for decision-support (Boggia and Cortina, 2010;
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
82 developed to assess farming system sustainability (see, for example, some indicator-based
83 tools at farm level: 4Agro (Bertocchi *et al.*, 2016), IDEA (Zahm *et al.*, 2019), APOIA-NovoRural
84 (Stachetti Rodrigues *et al.*, 2010), MOTIFS (Meul *et al.*, 2008), SAFE (van Cauwenbergh *et al.*,
85 2007), RISE (Häni *et al.*, 2003)). Most of the existing approaches assess farming systems
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,
89 2010; Gasparatos, 2010; Gasparatos *et al.*, 2008). Sustainability is a matter of perspective
90 and relevant criteria often depend on the local context (Zhen and Routray, 2003; Reed *et al.*,
91 2006; Bond *et al.*, 2011; Lairez *et al.*, 2016; Lele and Norgaard, 1996). For example, in a case
92 study of Danish maize value chains for German biogas, Gasso *et al.* (2015) compared key
93 sustainability criteria identified by stakeholders with criteria identified in generic
94 frameworks. They showed that the generic frameworks covered context-specific
95 environmental issues, but not context-specific socio-economic issues. Other sustainability
96 assessment methods overcome this weak point by considering farmer and/or stakeholder
97 perspectives to select evaluation criteria (e.g. Roy *et al.*, 2013; Coteur *et al.*, 2016; Coteur *et*
98 *al.*, 2018; López-Ridaura *et al.*, 2002; Ssebunya *et al.*, 2016; Yegbemey *et al.*, 2014;
99 Sydorovych and Wossink, 2008). Farmers are the key decision-makers, so their perspective is
100 essential. However, data collected from interviews alone are often inadequate for
101 quantifying and understanding sustainability issues (Fraser *et al.*, 2006). Moreover, the
102 span of a farmer's perspective can be incomplete in times of rapid change (Klapwijk *et al.*,
103 2014).

104 Expert advice and literature can also help inform the choice of quantitative verifiable criteria.
105 However, the scientific perspective of experts is not "pure knowledge" without
106 assumptions, values or preferred fields of interest (Sala *et al.*, 2015). de Olde *et al.* (2017)
107 showed that experts disagreed about what was reliable knowledge for assessing
108 sustainability and Smith *et al.* (2017) highlighted a disagreement in the research community
109 over the relevant indicators for assessing sustainability. Scientists have specific worldviews
110 that generate subjectivity in the evaluation (Lele and Norgaard, 1996). There is therefore a

111 need to go beyond expert and scientist consultations to select sustainability criteria using an
112 explicit procedure (Bosshard, 2000). The literature provides only a few examples where the
113 scientist knowledge used in generic frameworks goes beyond expert consultation to select
114 criteria and is based on a quantitative monitoring design (Reed, 2005). A selection of
115 relevant sustainability criteria with a transparent scientific diagnosis is needed, with a view
116 to understanding interconnected biophysical processes, especially in data-scarce regions.

117 In order to identify criteria and strengthen the dialogue to foster the co-designing of more
118 sustainable farming systems, it is necessary to bring together the perspectives of both
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
122 understanding of sustainability issues, by providing multiple ways of viewing a problem
123 (Bond *et al.*, 2011; Gough *et al.*, 1998; Creswell and Clark, 2017), and in allowing the
124 strengths of one method to offset the weaknesses of others (Creswell and Clark, 2017).
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
127 for a useful example). Most existing approaches integrating farmer and scientist
128 perspectives for sustainability assessment seek to select indicators to assess a predefined set
129 of criteria, assuming that sustainability is a generic concept defined with universal criteria.

130 The objective of our study was to identify relevant criteria for a sustainability assessment of
131 farming systems in northern Laos, with specific emphasis on combining farmer and scientist
132 perspectives and documenting how the criteria were chosen. The set of criteria identified
133 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
135 different farm types in the region. The specific objectives of this study were to (i) identify
136 farmers' objectives and to understand their priorities and perceptions with regard to
137 sustainability, for farm-level strategic resource allocation and plot-level tactical crop
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

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

156 summarized into lists of criteria. Eventually, these lists were aggregated into a final list of
157 sustainability criteria.

158 We carried out a card game in four villages (Lé, Xay, Leng and Dokham) and a group game in
159 three villages (Lé, Xay and Leng). Q-methodology was implemented in four villages that
160 captured farm and soil type variability (Lé, Leng, Nadou and Xay). Field monitoring for the
161 agronomic diagnosis was set up in three villages (Xay, Nadou and Leng) covering an area of 7
162 km² (Figure S1). The villages of Lé, Leng and Dokham were selected because an exhaustive
163 agricultural census was available describing all farm households using basic variables
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

168 We selected the Kham district in Xieng Khouang province located in northern Laos, close to
169 the Vietnamese border (19°38'N, 103°33'E; 605 m above sea level) (Figure S1, Supplementary
170 material) as a typical case of the market integration of farming systems with the
171 commercialisation of hybrid maize. Over the past two decades, farmers have switched from
172 extensive manually cultivated upland rice systems to cash crop systems with hybrid maize
173 cultivation, combined with the use of moto-mechanization, herbicides and mineral
174 fertilizers. This rapid switch to maize cultivation was favoured by the increase in maize prices
175 and in the demand for maize from the thriving livestock feed industry in Vietnam in the
176 2000s. Today, rural development stakeholders in northern Laos commonly believe that
177 maize cultivation is not sustainable and refer to it as 'resource-mining' agriculture with a

178 negative impact on the environment, i.e. leading to increased soil erosion, loss of soil fertility
179 and chemical pollution (Bartlett, 2016; ACIAR, 2014; Julien *et al.*, 2008). In the peer-reviewed
180 literature for Laos, maize cultivation was found to increase production costs
181 (Luangduangsitthideth *et al.*, 2018) and soil erosion (Dupin *et al.* 2009). In Thailand, Bruun *et*
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
186 support claims of environmental degradation (Lestrelin, 2010).

187 Our case study was located in the Kham basin, an area of Kham district where maize has
188 spread very rapidly because of relatively fertile and flat valleys with moderate elevation and
189 slopes (500 to 600 m asl). Lowlands are dedicated to rice cultivation and uplands to forest,
190 pastures and maize cultivation. Hybrid maize is sown once a year during the rainy season
191 (May-October) in sole stands without rotation with other crops. Cultivation starts in early
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
194 mounted on the rototiller used for paddy rice preparation. If applied, compound (NPK 16-20-
195 0) mineral fertilizer is used. The herbicides commonly used are atrazine (1-Chloro-3-
196 ethylamino-5-isopropylamino-2,4,6-triazine), paraquat (1,1'-Dimethyl-4,4'-bipyridinium
197 dichloride), and glyphosate (*N*-(phosphonomethyl)glycine). Europe banned atrazine in 2003.
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
203 than direct household interviews (Cash *et al.*, 2003). Farmers' objectives are connected to
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 farmers' objectives*

212 The aim of the individual card game, designed by the authors, was to reveal farmers' main
213 objectives at farm level with a five-year perspective. Following the approach of Berbel and
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
216 with time and circumstances" (Berbel and Rodriguez-Ocana, 1998). Values fall into four
217 categories (Gasson (1973): 1) *Instrumental values*, e.g. maximizing income, saving income or
218 expanding business. (2) *Social values*, e.g. belonging to a farming community, maintaining
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.

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

227 The game was composed of three sets of cards: "activity cards" representing farming
228 activities, such as paddy rice, maize, cattle or off-farm job; "asset cards" representing assets,
229 such as a motorbike or a sowing machine, and "bonus cards" representing extra resources,
230 such as a labour workforce, land and money (Figure 2A). In a first step, the farmers were
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
234 the reasons for the farmers' decisions and illustrated the changes by adding or removing
235 activity and asset cards. The farmer was invited to validate or modify the deck to get
236 accustomed to the use of the cards. The card combination at the end of the game
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,
241 the interviewer displayed the corresponding bonus cards. Bonus cards were useful to avoid
242 finishing the game with only a list of farmers' constraints rather than farmers' objectives. In
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
245 was then shown to the farmer, who validated it and the interviewer asked the farmer to

246 choose the three most important objectives. The results per objective were gathered for the
247 four villages. The researchers then selected objectives as relevant criteria when more than
248 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
251 crop to grow on uplands. The game is called TAKIT and was created by Ornetsmüller *et al.*
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
254 facilitator introduced themselves with this statement: "I am a trader and I have the best upland
255 crop ever, what question would you like to ask me, in order to know if you would grow it or
256 not?". Questions could only be answered with "yes" or "no". The TAKIT game had four
257 steps. The first step was a warm-up phase to explain game rules: two bottles were shown,
258 one with water and the other with an unknown yellow liquid. Participants were asked to
259 state the questions they would ask to know if they would drink the unknown yellow
260 beverage. The questions were written, collected and sorted according to their similarity.
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
263 heard the answers. This first warm-up step was crucial to introduce the second step in which
264 the yellow beverage was replaced by a fictional crop as it helped farmers to understand how
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
267 above. Farmers based their choice to grow the crop on the answers given by the facilitator
268 to their questions. The third step was a ranking of the previous questions. The questions

269 were presented on a board and participants chose their three most important questions by
270 ranking them from most (score=3) to least (score=1) important. The fourth step was a
271 discussion to identify farmers' criteria underlying their questions. For further details on the
272 TAKIT methodology, the reader can refer to Ornetsmüller *et al.* (2018). Eventually, questions
273 were grouped per village and an aggregated score was given to the questions by summing
274 the scores given by farmers. The researchers selected questions with a score above one and
275 aggregated them into a relevant list of criteria.

276 *Soil fertility perception: Q-methodology*

277 Q-methodology was not directly used to identify criteria, but rather as a complementary
278 method to deepen our understanding of the farmer discourses used to select criteria during
279 the group game and the individual card game. The group game revealed that farmers were
280 concerned with soil fertility when deciding which crop to grow (See section 3.1.). We used a
281 Q-methodology design (Brown, 1993) to study farmers' subjective perspectives when dealing
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
286 19 farmers in four villages (seven in Leng, five in Lé, four in Xay and three in Nadou). The
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)

292 disagreed with and iii) were neutral, doubtful or undecided about. The farmers were then
293 asked to read the 47 cards and place them on the floor following a design that mimicked a
294 normal distribution (Figure S2 in Supplementary material). The design had to be filled
295 incrementally from left with cards they mostly disagreed with (score of -5) to right with cards
296 they mostly agreed with (score of +5).

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

303 2.4. Researcher perspective: agronomic diagnosis

304 *Field monitoring network*

305 To identify plot-level sustainability criteria, farmer-managed fields were monitored from
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
310 knowledge on soils, climate, and crop management. We gathered groups of 10 farmers in
311 three villages to draw up these participatory maps. The fields were then selected to ensure
312 that they belonged to farmers from the three villages and covered the range of farm types,
313 soil types and management diversity identified during participatory mapping. Plot size was

314 set to 16 m² (to minimize within-plot heterogeneity, while keeping an area large enough to
315 ensure reasonable measurement accuracy) and included 4 to 5 planting rows with a length
316 of 3 to 5 m. We monitored 38 plots in 2016, 38 plots in 2017, and 35 plots in 2018 (n=111).
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.

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

329 *Analysis of variability in agronomic and environmental performance at plot level*

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

334 The relative yield gap, water stress, nitrogen balance (N balance), nutrient deficiency, weed
335 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 (Y_w)
337 yields of the 111 monitored plots that informed the relative yield gap calculation. Y₀ is the
338 yield achieved when water and nutrient supplies exceed crop requirements and biotic
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). Y_w is similar to Y₀, 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
346 variables related to environmental performance (Table 2).

347 A first analysis looked at relating maize yield to the variables deemed important for
348 agronomic performance (Table 2), i.e. single factor linear regressions of yield against water
349 stress, potential N balance, and pest/weed scores. In a second analysis, two classification
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
354 yield-limiting and yield-reducing factors were set as explanatory variables: highest weed
355 score, maize planting density, N balance and soil type. The second CART was performed with
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
358 variables: i) weed management with 'false seed-bed', i.e. ploughing, letting weeds grow for

359 one month and ploughing again (or herbicide spraying); ii) amount of work devoted to
360 manual weeding; iii) sowing hole density at emergence; iv) number of days between last
361 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 informed
363 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 farmers' objectives*

367 For respectively 83% and 80% of farmers, the objectives “be rice self-sufficient” and “have
368 high incomes for savings” were the most important objectives (Table 3). The objectives
369 “reduce work and effort” (77%), “have small regular incomes monthly for family
370 expenditures” (77%), “diversify income” (63%) and “reduce cash-flow needed” (33%) were
371 also frequently mentioned. A substantial share of farmers valued objectives related to
372 sustainability: “transfer a viable farm to the next generation” (27%) and “avoid herbicides”
373 (23%).

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

376 1) “Farm income - amount, consistency, cash-flow and risks”, synthesized 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”, synthesized from the objectives “diversify income” and
380 “obtain incomes during the dry season”
- 381 3) “Workload peak and drudgery of work”, synthesized 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
389 was not included as a criterion itself. The objective “preserve a traditional activity” was not
390 used as a criterion because (i) it was mentioned by only a small number of farmers (7%) and
391 (ii) “traditional activity” would be hard to quantify. We did not consider the objective
392 “perform activities that are easily manageable” as a specific criterion, but it was included in
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*

399 Important attributes for choosing a crop differed between villages (Table 3). The two most
400 important attributes for choosing a crop were i) suitability for village soil types and ii)
401 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
403 importance of soil fertility improvement for farmers, despite great variability between
404 villages (score of 27 in Leng, 6 in Lé, while soil fertility was evoked through the ability of the
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
410 work with too many interventions. The storability of harvest originated from the farmers’
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?”)
- 421 4) Work productivity and drudgery (from the questions “Is it easy to grow?” and “Does
422 it require a lot of labour?”)
- 423 5) Soil fertility (from the questions “Does it improve the soil?” and “Is it suitable for
424 village soils?”)

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

429 The TAKIT game, although played to identify plot-level criteria, informed the identification
430 of a farm-level criterion “farm autonomy”. Farm autonomy was related to the questions
431 “Can we use it for our own consumption?” and “Is it storable”. Farmers were willing to
432 cultivate upland crops to reduce food purchases (meaning lower autonomy) and farmers
433 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),
437 “Soils in flat land cleared from very old forest remain fertile even after 15 years of maize
438 cultivation”(63% of farmers), “When there is enough rain, most of the soils of the village are
439 still able to give good yields”(42% of farmers), “If the soil is deep, I know for sure that the soil
440 is fertile”(47% of farmers), “Low crop yield in a good climatic year is an indicator of low
441 fertility”(47% of farmers). They disagreed on three statements (Table 4): “Infertile maize
442 fields have a lot of weeds” (63% of farmers), “Soils are more exhausted than before, but
443 could give more yield today thanks to mineral fertilizer, a good variety and herbicide” (42%
444 of farmers), “Low maize density is the main cause of low yield compared with low soil
445 fertility” (42% of farmers).

446 We identified three contrasting opinions about soil fertility. *“Progressive-minded”* farmers
447 (opinion 1-O1, Table 4) agreed that (i) “Legumes can improve soil fertility” and (ii) “If the soil
448 has a black colour, it is a fertile soil, and if the soil is red or yellow it is an infertile soil”, and
449 (iii) “Soil fertility has decreased because of ploughing every year”. They disagreed with
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
454 disagreed with “It is not worth it to invest time and money in soil fertility”. By contrast,
455 *“Income-minded”* farmers (opinion 2-O2, Table 4) attached more importance to soil
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
458 was not only equivalent to high yields for them, they disagreed strongly with “No matter the
459 colour and the structure of the soil, a fertile soil has a high yield without adding mineral
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
463 erosion leads to a decline in fertility because the most fertile layer disappears” (most agreed
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
466 the soil less fertile”. The identification of *“progressive-minded”* farmers showed that soil
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.

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

477

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

484 3.2. Agronomic diagnosis

485 Constraints and sustainability issues possibly occurring in maize areas, as found during a
486 review of local knowledge and used to set up field monitoring, can be found in
487 supplementary material, Table S2. Farmers distinguished three soil types during
488 participatory mapping: red-sandy soils (low yields), loamy-clayey soils (medium to high
489 yields) and yellow sandy soils (medium to high yields). Farmers identified three types of crop
490 management: high-input intensified systems (mechanical sowing, harrowing after ploughing,
491 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)
498 depending on slope, type of sowing (mechanical or manual), amount of herbicide use, and
499 time between soil preparation and sowing. Clayey-loamy soils, the dominant soil type in the
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)
505 was more than three times the recommended dose, whereas it was equal to 0 for cropping
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
510 land, mechanical sowing on low-fertility sandy soils, medium period of bare soil). Risks of
511 erosion were either due to slopes or due to a long period between ploughing and sowing.
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

514 soil period before crop installation and the latter a long period, due to a false seed-bed
515 practice to reduce weed pressure.

516 The average potential (Y_0) and water limited (Y_w) 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 Y_0 and Y_w 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
520 basin had a total annual rainfall of 854, 875 and 1569 mm in 2016, 2017 and 2018,
521 respectively. The observed maize yields (Y_a) in the monitored plots were markedly below Y_w
522 and highly variable. Y_a 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%.

525 Field monitoring revealed the prevalence of weed infestation to explain yield variability,
526 itself mainly explained by sowing hole density. Yields were correlated to “Highest weed
527 score” ($R^2=0.19$, $P<0.001$) and potential N balance ($R^2=0.08$, $P<0.005$). Weed infestation was
528 significantly correlated with sowing hole density (Figure 3). When dealing with crop
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
531 dropped one seed per hole. Therefore, for the same sowing hole density, manual sowing led
532 to a plant density double that achieved with the seed drill, but with the same space (and
533 light for weeds) between holes. Sowing hole density varied greatly from 1.1 to 8.1 sowing
534 holes m^{-2} . A higher sowing hole density was achieved with mechanical sowing compared
535 with manual sowing (Figure 3B), but only 4% of farmers achieved the optimum sowing hole

536 density of 7.1 plant m⁻² enabled by the seed drill. Pest stress was not identified as an
537 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
541 plant density. The average relative yield gap was 59% for plots with “Highest weed scores”
542 above 4.8, and 45% for plots below 4.8. For plots with a high weed score, Yr was 69% when
543 the potential N balance was below -78 kgN ha⁻¹ and 54% when the N balance was above that
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
547 (R²=0.47).

548 The key outcomes revealed by the agronomic diagnosis were: i) high yield variability, high
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
553 because of a negative N balance in maize plots. The latter can be explained by the fact that
554 maize fields were used for cattle roaming in the dry season and the manure collected at
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”.

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

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

567 *Plot-level sustainability criteria*

568 Figure 5 shows the final set of criteria resulting from an integration of farmer and scientist
569 perspectives. Every criterion identified can be quantified with indicators. On the left-hand
570 side of the figure, the final plot-level criteria are displayed combining the serious games and
571 Q-methodology results with the agronomic diagnosis: economic performance, land
572 productivity, susceptibility to pests, weeds, diseases and climate variability, work
573 productivity and drudgery, soil erosion, herbicide risks, biodiversity, soil fertility, and
574 resource use efficiency. To establish this final list, the criteria originating from the serious
575 games were grouped with those from the agronomic diagnosis, e.g. “economic
576 performance” includes gross margin (derived from the TAKIT game), return on investment
577 (derived from the agronomic diagnosis and the TAKIT game) and cash flow (derived from the
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
581 serious games and Q-methodology results with the agronomic diagnosis: farm income
582 (amount, consistency, risk and cash flow), diversity of activities (risks), workload peak,
583 drudgery of work, farmer autonomy, rice/forage self-sufficiency, fertility transfer, and
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
592 security was crucial. This was foreseen, given the high poverty incidence among farmers in
593 the study region (Coulombe *et al.*, 2016). However, long-term concerns were not completely
594 ignored by the farmers. The importance given to soil fertility in the serious games may,
595 however, have been due to a desirability bias, i.e. the tendency of farmers to answer
596 strategically to be favourably perceived by the interviewer (Lusk and Norwood, 2010;
597 Wheeler *et al.*, 2019). We tried to minimize this bias by presenting ourselves as researchers
598 from an international agricultural research centre and did not put any particular emphasis
599 on technologies related to soil fertility improvement. The importance given to soil fertility
600 improvement may also have expressed the farmers' desire to achieve high yields rather than
601 long-term productivity. The results of the Q-methodology, however, weakened such a

602 hypothesis, because some of the farmers were concerned by soil fertility degradation and
603 wanted to preserve it for the next generation. The farmers' long-term objective to transfer a
604 viable farm to the next generation, identified during the card game, suggests that after 20
605 years of maize monoculture, farmers were concerned about the sustainability of maize-
606 based systems. Unravelling the factors driving maize cropping system sustainability was
607 crucial.

608 *Drivers of cropping systems sustainability with the agronomic diagnosis*

609 Maize cropping system performance varied widely, but single factors (weed and pest
610 competition, N balance, and water stress) explained only 19% ($r^2=0.19$) of the variations (at
611 best) and CART 37% (at best). Substantial remaining unexplained variation is, however, a
612 common feature of on-farm trials in a smallholder context (Baudron *et al.*, 2012; Falconnier
613 *et al.*, 2016; Naudin *et al.*, 2010). An unexpected result of field monitoring compared to the
614 local discourse (see Table S2 in Supplementary material) was the predominance of weed
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
617 found in the region (Epper *et al.*, 2020), but weed pressure and plant (and sowing hole)
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
621 large soil clods and could have prevented the seed driller from operating properly. Sub-
622 optimum soil conditions can be due to: i) limited access to ploughing services, compromising
623 the timeliness of the operations and ii) a short time window for rice and maize
624 establishment, with farmers focusing on rice cultivation, hurrying maize sowing to spare

625 time for paddy rice preparation. Beyond yield variability, poor crop establishment also
626 favoured detrimental environmental impacts, such as herbicide overuse to control weeds,
627 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
630 diagnosis is a methodology easily applied by an experienced agronomist trained to
631 implement it quickly over one or two cropping seasons. However, in line with our objective
632 to publish a scientific paper, plot monitoring was carried out over three cropping seasons,
633 i.e. a long period for a prior analysis to guide the design and implementation of sustainable
634 options for farmers. Field monitoring was necessary to dismiss preconceived ideas (i.e. low
635 yields are due to poor soil fertility) and to explain the drivers of sustainability (see section
636 4.2). Moreover, the quantitative data collected on maize cropping systems were crucial for
637 multi-criteria assessment at farm level and were the basis for the quantification of indicators
638 at that level.

639 4.2. Added value of our approach combining two perspectives

640 We identified some pitfalls of existing broad-based methods for our case study, namely i) a
641 lack of integration of multiple perspectives (farmers, experts and scientists) to identify the
642 sustainability issues at stake, ii) an insufficient consideration of the local context for criteria
643 selection, and iii) a lack of transparency regarding the scientific logical reasoning that led to
644 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
647 study, integrating knowledge from scientists and farmers with a mixed-method approach
648 made it possible to embrace the plurality of views on sustainability. Scientific analyses at
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
654 lacked farm-scale contextualization integrating farmers' decisions and constraints; ii)
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
659 fertility contrasted with current soil management associated with negative N balances and
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'
664 perspectives and agronomic facts: farmers generally disagreed with the statement "Low
665 maize density is the main cause of low yield compared with low soil fertility" (See section
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
668 complement farmers' perspective was the three criteria not explicitly mentioned by farmers

669 in the serious games and Q-methodology: erosion risks due to bare soil, low sowing density
670 leading to risks of high weed pressure, herbicide overuse and leaching risks due to weed
671 pressure. Van Asten *et al.* (2009) showed that farmers struggle to identify yield-constraining
672 factors when constraints are uniform in time and space. Co-learning cycles engaging farmers
673 and researchers, with quantitative field monitoring and feedback sessions, can contribute to
674 the convergence of farmers' and scientists' views (Falconnier *et al.*, 2017, Hanna *et al.*,
675 2014).

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

683 *Consideration of the local context to select criteria*

684 We compared our final set of criteria with some other sets used in existing generic methods
685 (Gomiero and Giampietro, 2001; Dalsgaard and Oficial, 1997; Liebig *et al.*, 2001; Hassall *et al.*,
686 2005; Waney *et al.*, 2014; Castoldi and Bechini, 2010; Meul *et al.*, 2008). Some of our criteria
687 were similar (e.g. erosion, pesticide use, productivity), but some issues would not have been
688 well covered with a generic framework. For example, at plot level, a pre-defined set of
689 criteria would have missed the relevance of the criteria "resource use efficiency" or "crop
690 sensitivity to weeds" as identified with field monitoring. A focus on soil fertility, as

691 emphasized in most existing methods, would certainly have hidden the importance of other
692 yield-constraining factors, such as weed infestation linked to sowing density and appropriate
693 crop establishment.

694 *Transparency regarding scientific logical reasoning*

695 Scientific objectivity did not lie in the fact that science brought our understanding closer to
696 "pure knowledge" devoid of subjectivity (Alrøe and Kristensen, 2002), but rather lay in the
697 transparency of the methodology used and the assumptions made. In our case study,
698 transparency was reached because we answered a particular question in view of a specific
699 objective, and explained the choices made for abstraction of the system assessed, and the
700 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
703 assumptions, values or preferred fields of interest (Sala *et al.*, 2015). Indeed, 20th century
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,
706 1987). The aim of in-field monitoring was to go beyond facts that were generally accepted by
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.

709 In developing countries, where farms have shifted from subsistence to market-oriented
710 systems, sustainability evaluations are challenging. Quantitative data are scarce, or lack
711 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.

724 We found that, beyond the standard socio-economic criteria expected for poor farmers,
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
727 monitoring showed that the ability of farmers to ensure good crop establishment was a
728 strong determinant of maize system sustainability. Today in the Kham basin, while it is true
729 that maize-based cropping systems are facing serious sustainability issues, our diagnosis
730 revealed that it is mainly inadequate crop management during crop installation that leads to
731 low resource use efficiency and unsustainable trajectories.

732 The approach presented here is useful for understanding farming system sustainability
733 based on local priorities, as perceived by farmers and scientists. The approach can assist the

734 design of multi-criteria assessments of alternatives to the current maize-based cropping
735 systems and contribute to informing priority-setting for institutional development and
736 agricultural policies in the region.

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747

748

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1059

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	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	m ² 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	% ₀		
- Total phosphorus	% ₀		
- 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		

1061

1062

1063 Table 2: Variables used to explain plot-level agronomic and environmental performance (with units in
 1064 brackets). Y_w : potential water-limited yield, Y_a : observed actual yield, LAI_w : Leaf Area Index, water limited,
 1065 LAI_0 : potential Leaf Area Index, Y_0 : potential yield, N_{min} : nitrogen mineralized from total soil organic nitrogen
 1066 ($kg\ ha^{-1}$), N_{fert} : amount of mineral nitrogen applied ($kg\ ha^{-1}$), N_{uptake} : nitrogen uptake from soil by maize (kg
 1067 ha^{-1}), $N_{totSoil}$: total soil organic nitrogen ($kg\ ha^{-1}$)

	Calculation	Type of indicator computation
Agronomic performance		
Relative yield gap (%)	$(Y_w - Y_a)/Y_w * 100$	Direct measurement; PYE model simulation
Water stress (-)	LAI_w/LAI_0 Y_w/Y_0	PYE model simulation
Potential nitrogen balance ($kg\ ha^{-1}$) <i>Quantity of nitrogen potentially left in the soil for maize yielding at water-limited potential</i>	$N_{min} + N_{fert} - N_{uptake}$ Where - $N_{min} = (30/20) * 68 * [N_{totSoil}]$ if $pH > 7$ and - $N_{min} = (30/20) * 0.25 * ([pH] - 3) * 68 * [N_{totSoil}]$ if $pH < 7$ (QUEFTS model, Sattari et al. 2014) - $N_{uptake} = Y_w * 21$ (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)	$HTI = (\text{applied dose}) / (\text{recommended dose} * \text{area of the field})$	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

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
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	Score
	"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?"	
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

1071 *the question was mentioned in the preliminary steps but no farmers finally ranked it as important.

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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
 1092 varimax rotation (see section 2.2). Only the statements that created the most distinguishing classification
 1093 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
<i>Crop management and soil type</i>					
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
<i>Indicators of environmental performance</i>					
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

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Researcher perspective



Farmers' perspective

Field-level agronomic diagnosis



Analysis of farmers' objectives

Field monitoring network:
small plots in farmers' fields

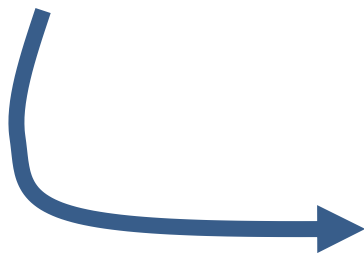


Playing serious games
+ Q-methodology



Quantitative data on determinants of
cropping system sustainability

Farmers' perceptions of
sustainability



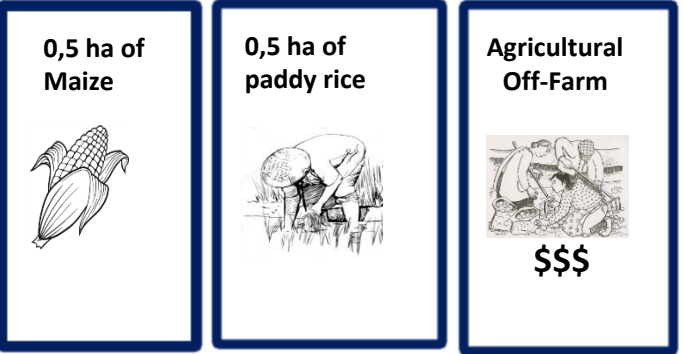
**Set of locally relevant
sustainability criteria**



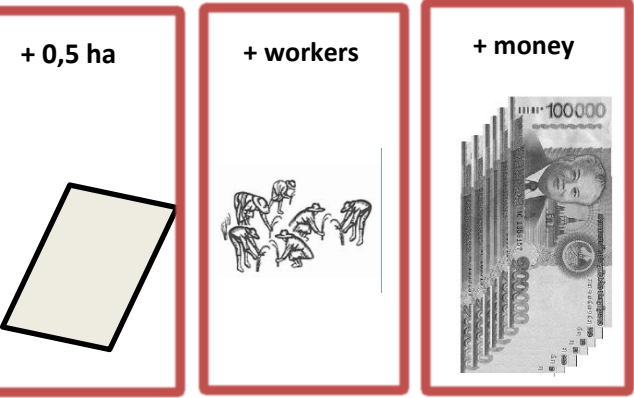
Multicriteria assessment

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

A Farm activities cards



Bonus cards



B



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)

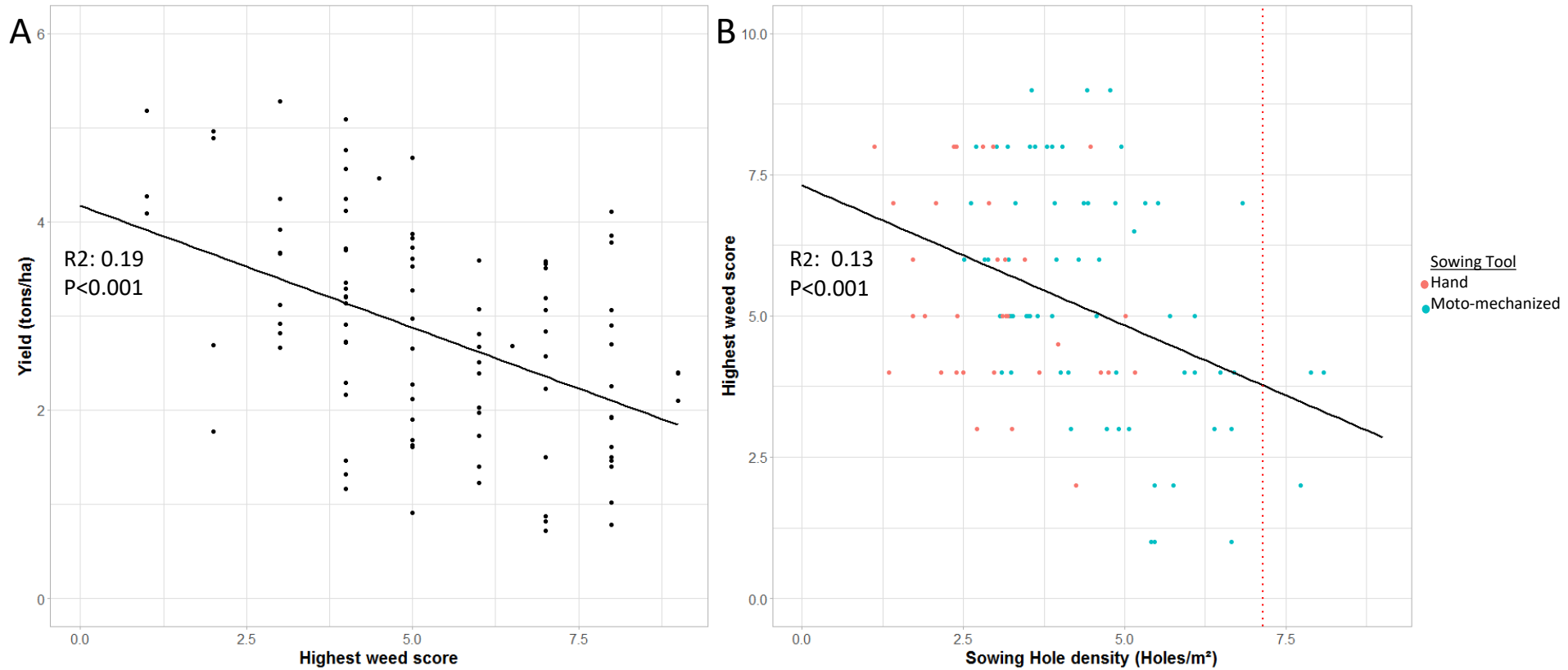
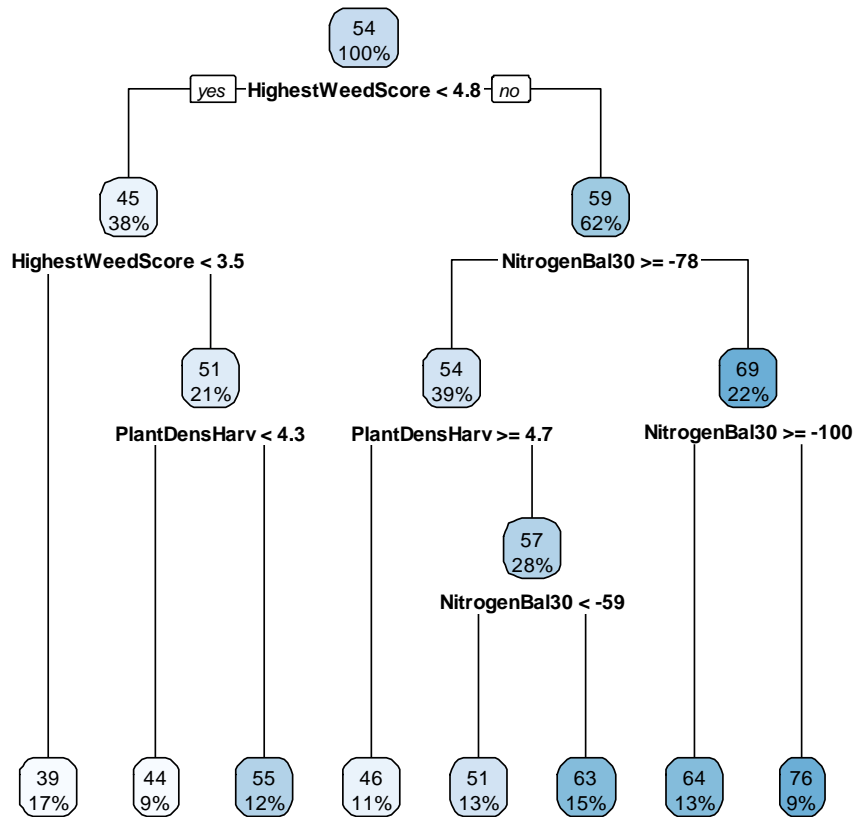


Figure 3: Effect of highest weed score on maize grain yield (3A) and effect of sowing hole density on highest weed score (3B). The red dotted line (3B) is the optimal sowing density allowed by the seed drill (7.1 plants m⁻²)

A



B

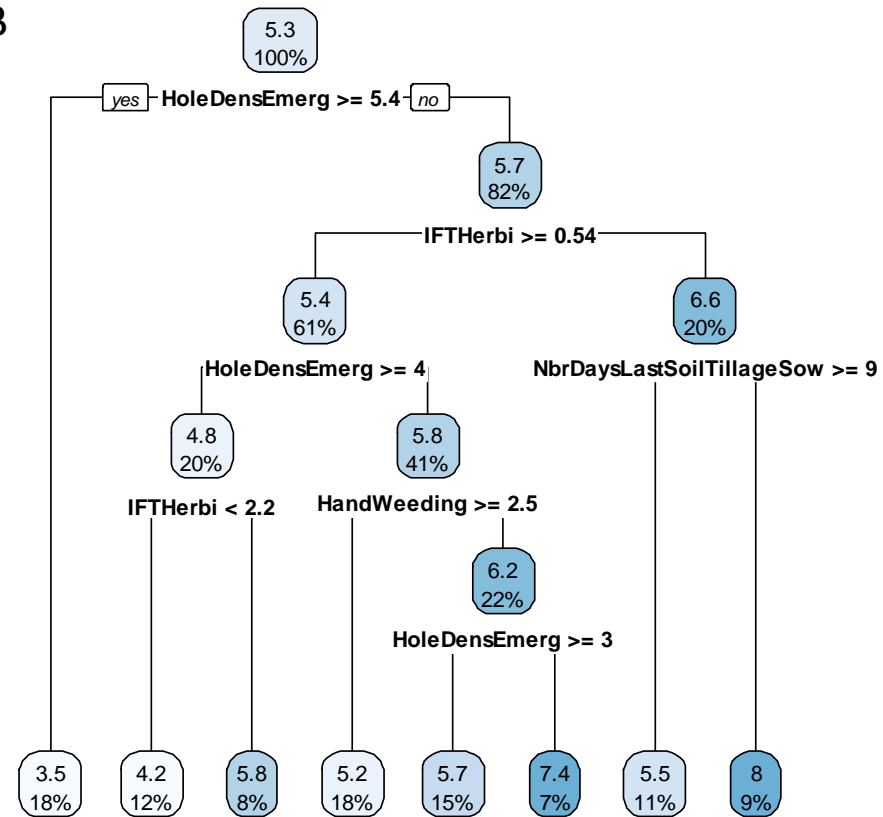


Figure 4: Classification and regression tree models to describe relative yield gap as a function of yield constraining variables (A), and highest weed score as a function of technical management variables (B). In each box, the predicted value is on top and the percentage of observations below. *highestWeedScore*: 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.

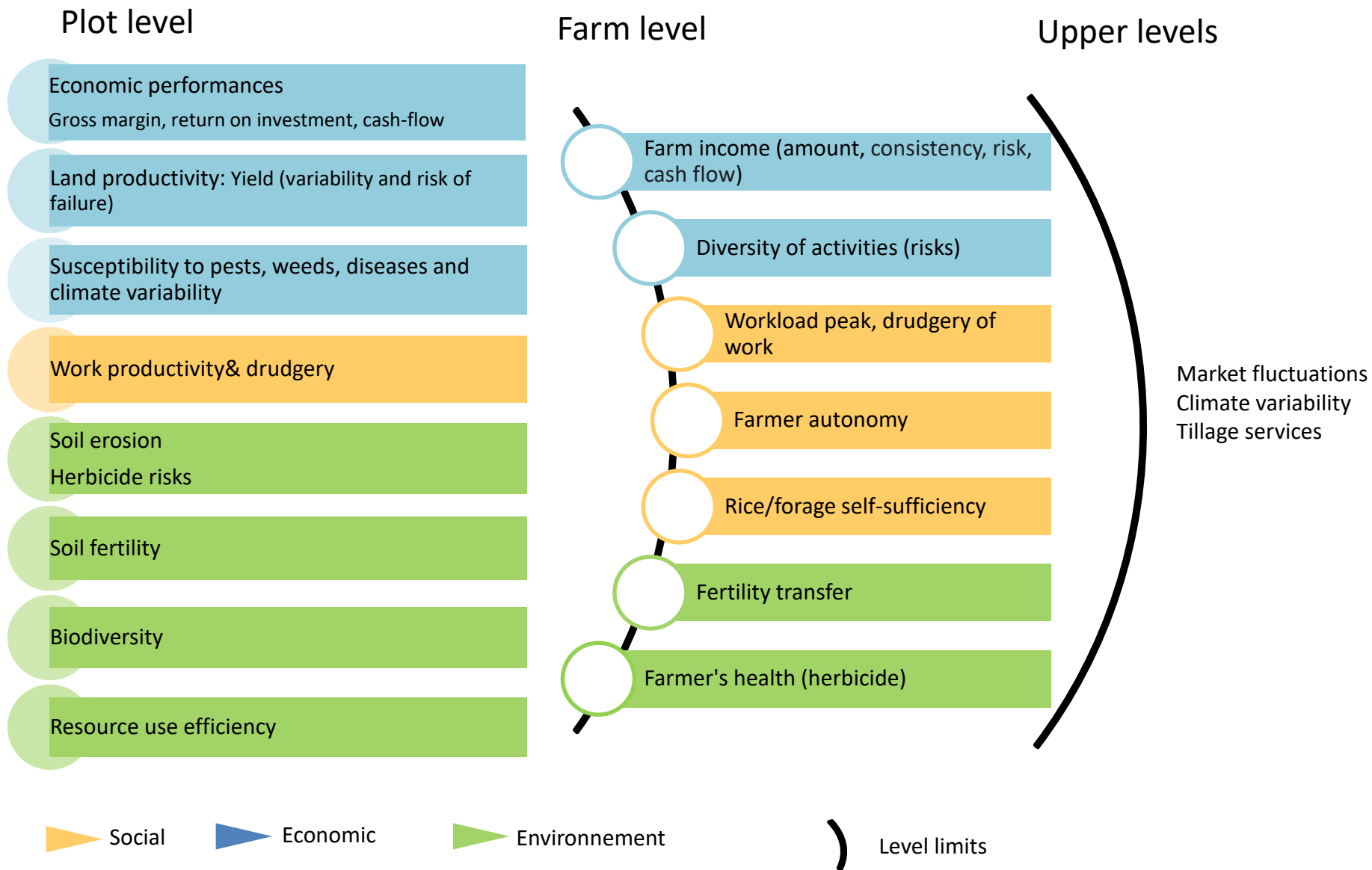


Figure 5: Final set of locally relevant criteria. The reader is referred to the web version of this article for interpretation of references to colors.